THE KILN DRYING OF LUMBER

A PRACTICAL AND THEORETICAL TREATISE

BY

HARRY DONALD TIEMANN, M.E., M.F.

IN CHARGE, SECTION OF TIMBER PHYSICS AND THE KILN DRYING EXPERIMENTS OF THE U. S. FOREST SERVICE. SPECIAL LECTURER IN WOOD TECHNOLOGY AND FORESTRY, UNIVERSITY OF WISCONSIN. FORESTRY PRODUCTS LABORATORY, MADISON, WISCONSIN

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PRECAUTIONARY NOTICE

Wood which has been bent in iron forms should not be steamed again after the forms have been removed, but the drying should be started at once at a humidity less than saturation. Bent wood is in a peculiar condition due to the internal stresses introduced in the bending, and if steamed again after it has become " set " the fibers will soften up to such an extent that the wood will warp out of shape or even rupture on the tension side. This caution applies particularly to heavy pieces, such as bent oak wagon rims. When bent wood, after it is dry, is steamed, it will tend to resume its original form with considerable force. Bent wood should therefore not be steamed for removal of casehardening.

H. D. Tiemann.

October 18, 1917.

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CHAPTER I

Introduction

THE OBJECTS OF DRYING WOOD AND THE NEED OF A TECHNICAL KNOWLEDGE OF KILN DRYING

Wood, next to stone, is doubtless the earliest material used by man and has served his needs more than any other substance. In fact, it is safe to say that civilization could not exist were it not for the forests and the wood derived therefrom. Kingdoms have risen and fallen and become extinct, as the forests have flourished, been wantonly destroyed and perished. In China, for example, in the Shan-Si and in the Chi-Li Provinces, and near Fou-Ping, vast regions, once thickly populated, are now desolate wastes or wholly uninhabitable through the prodigal destruction of their greatest source of prosperity—the forests which once clothed the steep mountains, preventing floods and erosion, the washing away of the fertile soils, and which furnished fuel and building material in abundance. In the Southern Alps and in the Pyrenees Mountains, in Europe and Greece, and in Northern Syria

and Palestine, and in Northern Africa, the same results have followed the loss of the forests. Through heroic efforts and vast expense France and Italy have been reëstablishing the habitability of the land by replanting.

But it is not with the living tree that our present subject has to do—all of that belongs to the province of Forestry—but rather with the product after the tree has been cut down and sawed into lumber or other forms of wood. Lumbering and Forestry are not antitheses, but both should accomplish the same result, the perpetuation of the forest for future use, whatever that may be. Lumber is a crop, as are vegetables, and the forest may be utilized, and at the same time conserved for future use.

TABLE I.—CONSUMPTION OF WOOD IN CUBIC FEET PER CAPITA IN VARIOUS COUNTRIES BEFORE THE WAR (INCLUDING FIREWOOD).

From Forest Service Bull. 83, Forest Resources of the World, by Raphael Zon.

	Cu. Ft.		Cu. Ft.
United States	260.0	Japan	30.0
Canada	192.0	France	24.6
Norway	125.0	Denmark	19.8
Sweden	120.0	Belgium	17.7
Finland	91.5	United Kingdom	14.0
Russia	63.0	Holland	13.1
Austria-Hungary	57.0	Italy	13.0
Switzerland	38.0	British India	0.8
Germany	36.6		

To give an idea numerically of the intimate relation which wood bears to every individual, the table above is inserted, which shows, before the Great War, what

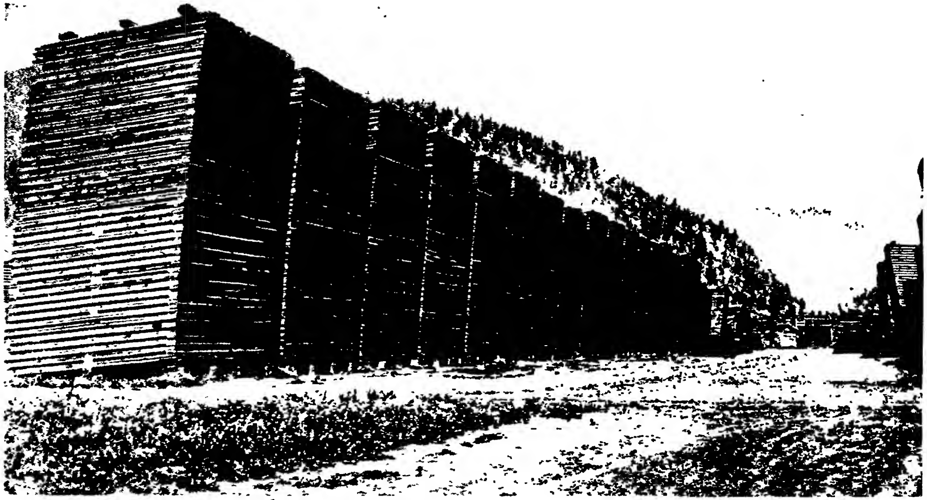


FIG 1.—Row containing five hundred thousand board feet of Douglas fir and Western larch stacked in the yard for air drying, at Bonner, Mont.

the relative consumption of wood per capita has been in various countries.

It is evident that wood in the living tree contains a great deal of moisture. In fact, the walls of the cells of which the wood is composed, as we shall see later on, are saturated and never become dry in the natural state. Trees contain anywhere from 30 to over 200 per cent. of the dry weight of the wood in water. This moisture renders the wood very heavy and unsuitable for use for most purposes. It must be got rid of before the wood will burn for fuel, and before lumber is used for houses or furniture or any manufactured article. For some uses, as piles, concrete forms, etc., wet wood is desirable, but in the vast majority of cases it must be dry.

When a tree is cut down and sawed into lumber, this will gradually dry in the air, if piled so the air can get at it, to a certain degree depending upon the average humidity of the climate, and is then called in general terms "air dry" (Fig. 1). This condition will range from 8 to 18 per cent. of water, based on the perfectly dry weight, according to the climate and time of year. In the neighborhood of New York City this condition will average about 14 per cent. during the summer time, if protected from the rain and dampness. It takes a long time for wood to become air dry, depending upon the species, the thickness of the boards, the

initial amount of moisture, and the manner of exposure and the climate. One-inch white oak, for instance, will require from one and a half to three years to thoroughly air season; white pine, on the other hand, may thoroughly dry in four months. If left in the log it will require many years for the water to evaporate, especially if the bark remains on. In fact, except for very durable species, as cypress or white oak, the wood is apt to completely decay before it becomes dry, in the log form.

All wood in drying shrinks and is, therefore, liable to warp and check. Moreover, the strength of the wood substance greatly increases as it dries below the "fibre saturation point," which is the name given to the condition of the wood when the cell walls become saturated with moisture (about 25 to 30 per cent. of the dry weight).

Briefly, leaving out the use of wood as fuel, the objects of drying wood may be summed up as follows:

1. To render it suitable for the purpose for which it is to be used.

2. To lessen the weight for handling and shipping purposes.

3. To prevent decay.

4. To increase its hardness and strength, and to prevent subsequent shrinkage and "working" after it has been placed in a building or manufactured article.

For many purposes, such as use in heated buildings, cooperage, gun stocks, athletic goods, etc., "air dried" wood is not sufficiently dry, and it must be further dried by means of heat in a dry kiln. Furthermore, many woods, such as red gum, western larch, and southern oaks, seldom air dry without great losses in warping, checking, case hardening, and honeycombing. These losses may be greatly reduced or entirely eliminated by properly kiln drying the green material in kilns where the humidity and circulation and temperature can be maintained at the most suitable amounts. For some purposes, as flooring, cabinet work, etc., the "working," that is, the twisting of the wood due to swelling and shrinking under changes of the atmosphere, may be slightly reduced by thorough kiln drying.

The principal objects, therefore, of kiln drying instead of the slow process of air drying may be enumerated under the following headings:

1. To improve the condition of the wood for the purpose for which used.

2. To reduce losses which occur in air drying.

3. To reduce the time necessary to carry stock in the yard.

4. To reduce shipping weights without waiting for the long time required to air dry the material.

All kinds of methods have been tried and several

hundred patents taken out for apparatus, processes, and kilns, for drying wood. Many of these have not proved to be a success. The processes include preliminary treatments of steaming at atmospheric pressure and at pressures up to forty or even sixty pounds gauge, soaking in various solutions, drying in vacuum, in compressed air, in alternating compressed air and vacuum, in compressed air and steam, in superheated steam, and in gases such as waste products of combustion from chimneys, and even electrical treatments. Temperatures vary all the way from 60° F. up to 300° F. and even 400° F. in gases other than air.

Apparatus of all kinds have been tried, also, including steel cylinders, accordion-like heaters, ovens, and drying rooms of all shapes and sizes.

While some species, such as pine, fir, basswood and mahogany, are easy to dry, many others, as oak, gum, and notably eucalyptus (blue gum), are exceedingly difficult to dry, requiring totally different treatment.

A great amount of lumber is being kiln dried chiefly for the purpose of reducing shipping costs and for eliminating the investment necessary to carry a large stock on hand. This is particularly true with respect to the West Coast timbers, especially Douglas fir, and also of southern yellow pine. For this purpose the quickest possible method of drying consistent with not seriously injuring the sales value of the stock is sought

after, and high temperatures and superheated steam are largely used.

In 1913 it is estimated that the total cut of lumber in the United States (exclusive of poles, posts, hewn ties, and firewood) (sawed into lumber or timber at mills) was 38,388,110,000 board feet, and 88,984,000 additional was imported. The various ways in which this was used are given below:

Wood-using factories	24,576,557 M
Exports of lumber and timber (planks, sawed ties, etc.)	3,185,864 M
Consumed by railroads:	
Sawed ties	1,215,597 M
Bridge and trestle timbers	841,859 M
Miscellaneous sawed wood	28,804 M
Building lumber, studding, joists, rafters, and rough construction	8,628,413 M
Total less imports	38,477,094 M

Out of the 24,576,557M used in factories, an estimate made according to 54 distinct wood-using industries shows that approximately 15,116,000M softwoods and 4,725,000M hardwoods were kiln dried before using. The hardwoods are mostly first air dried and then put through the kiln. Many of the softwoods are dried directly from the saw. Assuming an average value of $16 for softwoods and of $21 for hardwoods, this figures out a value of $241,856,000 for softwoods which are annually kiln dried and of $99,225,000 for hardwoods.

The official estimate for the total lumber cut for 1915 is 37,013,294M, which is not greatly different

from that of 1913, so it is fair to assume that the figures hold throughout very closely for the present conditions. If the present losses in preliminary air drying, which amount to considerably over 12 per cent. for hardwoods and 5 per cent. for softwoods, could be reduced to 2 per cent. by the best methods of kiln drying direct from the green condition, there is a possible annual saving of $17,178,000 alone, not including lumber which is not now being kiln dried.

The value of a technical knowledge of kiln drying is, therefore, self-evident, and it is the purpose of this book to give the reader the best information available on this important subject. The United States is acknowledged to be in advance of all other countries in this particular phase of the wood problem.

Thus far, I have touched only upon the losses which it is possible to obviate to a large extent. Let us consider some of the positive advantages to be gained by better methods of drying.

In the first place, it would enable architects, engineers, and wood-users to specify what they required in regard to this condition of the wood with a degree of exactness, as is now done with other materials. How would it seem for an architect, for instance, to order edge grain western larch flooring for his building and to state that it should contain between 5 and 7 per cent. moisture, that it should have been manu-

factured only when it contained 5 per cent., that it should not be casehardened beyond a certain degree determinable by a simple test, be free from all checks or honeycombing, and that it should not have been heated beyond 160° in the dry kiln while it was moist in order to avoid brittleness. Who would accept such an order to-day? Yet when lumber dealers can come up to such standards, which is by no means a utopian idea, there will be little necessity to "boom" the lumber markets, for the customer will get just what he wants and be satisfied.

CHAPTER II

The Structure and Properties of Wood [1]

A technical discussion of the minute anatomy of wood as revealed by the microscope need not be given here, as it can be found in botanical works, but some idea of the structure and the way in which different species differ from one another is desirable for a clear understanding of the manner in which it behaves in drying. In general, wood is built up of individual "cells" of various shapes and sizes which have been formed by the "cambium" or the region of active growth, consisting of a thin layer of soft, succulent tissue lying between the inner bark and the wood proper. Every year this cambium deposits a new layer of wood upon the outer circumference of the central cylinder, thus forming the "annual rings" or the "grain" of the wood. In most trees the several last-formed outer layers remain active and conduct water and mineral substances from the roots upwards to the leaves. This is the "sapwood" of the tree. The inner layers of the sapwood, after they have functioned in this way for a number of years, finally be-

[1] For a more complete discussion of the properties of wood, the reader is referred to "The Economic Woods of the United States," by Samuel J. Record, Wiley & Sons, 1912; also to "Wood," by G. S. Boulger, Arnold, 1908. A complete list of references is given in Record's book.

come inactive and are converted successively into heartwood, which, so far as the living functions of the tree are concerned, is dead wood, but it still acts as a mechanical support to the tree. Certain chemical waste products are deposited within the cell walls from the living protoplasm in the sapwood as it becomes converted into heartwood, thus giving the usual darker color to this portion. In some species, as white beech, heartwood is never formed, and in others, as balsam fir, no change in color takes place. Several distinct kinds of cells are formed by the cambium layer in some species of wood, which are as a rule long and tapering, some being almost hair-like in shape and others much wider in proportion to length. These cells are arranged vertically in the tree, but in addition they are interspersed by numerous horizontal groups of thin-walled, pith-like cells arranged radially in the trunk in strands shaped somewhat like two-edged swords placed edgewise. These are the "medullary rays" (silver grain in quarter-sawed oak), and serve to conduct food and moisture from the sapwood and the bark to the growing cambium layer. It is on account of these medullary rays that wood dries more rapidly in the radial direction than in the tangential.

Nearly all woods may be classed into two principal groups, having very marked distinctions, with respect to the elements of which they are composed. The so-

called "hardwoods," or broad-leaved trees, more cor rectly the "angiosperms," are the more complex ii structure, whereas the commonly called "softwoods,' or needle-leaved trees, the conifers, or more correctl} the "gymnosperms," are comparatively simple. Th(former are called porous woods on account of th(tubular openings which they contain, known as vessels These vessels are entirely lacking in the gymnosperms In some woods, as red oak, these vessels are completel} open passages, so that air may readily be blown througl a stick of the green wood many feet in length. Ii others, such as white oak, for example, the tubes ar(blocked by ingrowths of thin-walled cells known a: tyloses. It is impossible on this account to force an} appreciable amount of air through a piece of fresl white oak even an inch in length. This is why whit(oak is such an excellent wood for tight cooperage whereas red oak would make a leaky barrel.

In addition to the vessels, hardwoods (angiosperms) contain several distinct types of cells.

Fig. 2 is a sketch from the actual microscopic view: showing a small block of one of the simplest of th(hardwoods, tulip or yellow poplar, as it would appeai if highly magnified. TT is a horizontal surface cu across the grain. RR is a radial surface (quarter sawed) and TG is a tangential surface (plain sawed) AR is one annual ring, S being the first formed layei

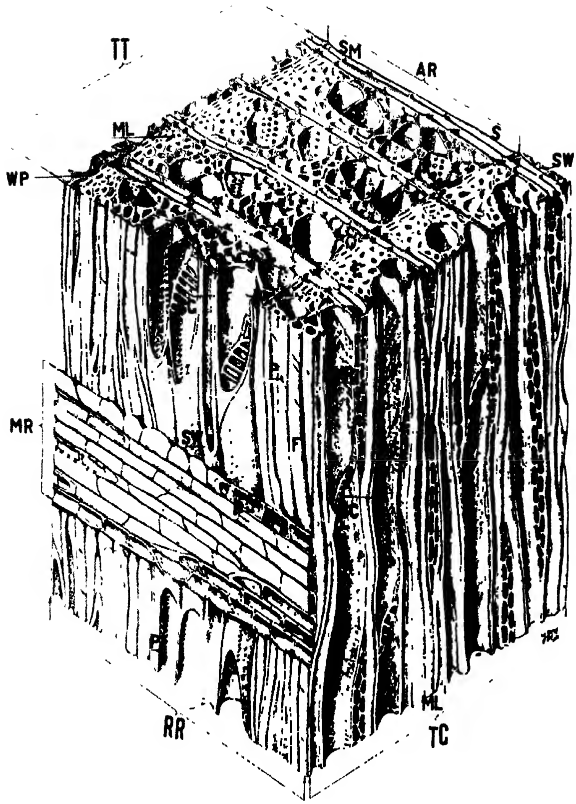


Fig. 2.—Highly magnified block of wood (hardwood).

or the springwood composed of large thin-walled cells, and SM the later formed layer of small thick-walled cells or summerwood. It is the relative thickness of the cell walls which gives the density and hardness to certain woods, as hickory, compared to thin-walled woods, as basswood, and which makes the hard part of the rings in yellow pine. MR and MR are medullary rays. V is a vessel cut in section and showing its remarkable end splicing on to the cell below by means of a scalariform grating. These grating-splices are shown in three places marked SC. They differ in form in different woods, in some, as birch, being simple, elliptical, or circular openings. The vessels communicate with adjacent vessels by means of numerous small partial openings called "bordered pits." All cells retain their individual walls, which become thickened as the cell develops from the cambium layer by successive depositions laid down on the inside by the living protoplasm. Adjacent walls between two cells are, therefore, composed of five distinct layers, the original thin primary walls of the two contiguous cells and an intermediate substance by which they are joined together. The two primary walls, together with the cementing substance, are collectively known as the "middle lamella." On either side of this "middle lamella" are the thickened walls of the two contiguous cells. The pits are openings in the thickened walls,

but do not pass through the middle lamella. While the pits serve as communicating regions for the protoplasm, they must not be considered as openings in the

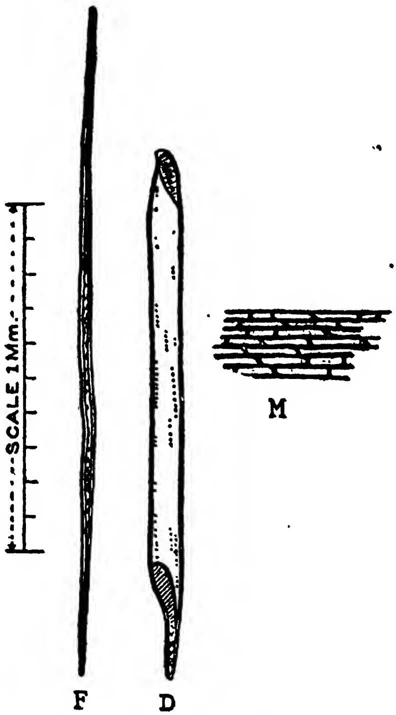


FIG. 3.—Comparative sizes of the wood elements of red gum. F, wood fiber; D duct or vessel (trachea); M, medullary ray cells. (Forest Service Bulletin 58. Drawn by the author.)

sense of punctures in the walls. Numbers of these "bordered" pits are shown on the walls of the vessels in the figure.

The other cells, which in this species are almost all "wood fibers" with thick walls and small cavities, are what give the rigidity and hardness to the wood. They are shown at F and ML. These wood fibers also have pits which are very small and slit-like. One is shown

FIG. 4.

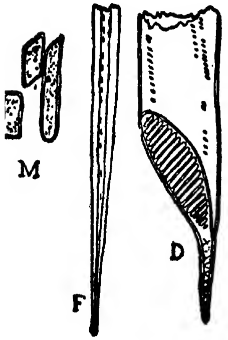


FIG. 5.

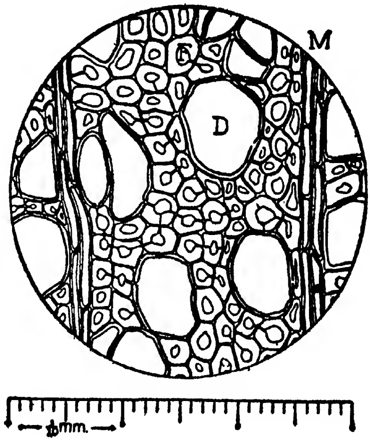


FIG. 4.—Highly magnified portions of the elements of red gum wood D, end of a duct or vessel (trachea), showing the peculiar grating; F, pointed end of a fiber; M, short medullary ray cells The narrow, slit-like pits are seen in the walls of each element

FIG. 5—Cross section of red gum wood, showing the structure. F, wood fiber; D, duct or vessel (trachea); M. medullary ray cells.

at P. Wood fibers vary in average lengths in different species from one to two millimeters.

Some idea of the relative sizes of the various cells in red gum, which is almost identical to tulip in structure, is shown in Figs. 3, 4, and 5 (from Forest Service Bulletin 58), which are sketches made by the writer directly from the microscope.

Oak is considerably more complex in structure than the woods described above, but for a more detailed description the reader is referred to works on wood structure.[2]

The gymnosperms or coniferous "softwoods," on the other hand, are much simpler in structure than the tulip just described. In the firs, for instance, the vertical cells are practically all of one kind, called tracheids, and are of approximately the same widths in the circumferential directions, though differing considerably in thickness, measured radially, from the large, thin-walled springwood cells to the small, thick-walled summerwood cells. In section they are nearly rectangular and are arranged in very even and uniform radial rows. The medullary rays are very small, numerous and uniformly arranged. This remarkable simplicity of structure gives to this class of woods certain properties which are lacking or less strongly marked in the other class. They are remarkably stiff in proportion to their weight, which renders the conifers especially suitable for building and structural purposes. Also, their resonance properties are good, so that they are used for sounding boards, etc., in musical instruments. In the pines especially, and also in spruce and larch, there are in addition to the tracheids many tubular openings called "resin ducts," in which the resin is stored and

[2] "The Oak," by Marshal Ward.

out of which it flows when the tree is injured or tapped. These resin ducts are not cells but are openings between the cells. The tracheids all have numerous, bordered pits. These bordered pits are of peculiar structure, deserving notice in considering the drying or impregnation of wood. The middle lamella extends straight across the round opening of the pits of the two contiguous cells like the membrane of a drum, the openings being always in exact alignment. Imagine two soup plates placed face to face with their rims touching, a membrane stretched across between them and round holes cut in the bottom of each, and a very good conception will be had of the shape of the bordered pits. The membrane has a thickened circular disk at its center which is larger in diameter than the two holes in the "borders." When wood dries this thickened disk, called the "torus," becomes pressed to one side tightly against the border, to which it firmly adheres, thus effectively sealing the opening of the pit. This phenomenon occurs chiefly in the springwood of the annual rings, since the pits in the summerwood portions do not as a rule become closed in this manner. Just how these remarkable structures behave in the conduction of water up the tree is not known, but they must have an important function in this regard, as they are present in all the water-conducting tissue.

In the pulp and paper industry these tracheids are indiscriminately spoken of as "wood fibers." But the true wood fibers belong to the hardwoods and are of quite a different form.

Trees native of tropical countries often do not have the annual rings, since their growth is more or less continuous, but even in hot countries irregular rings are sometimes formed, due to periodic seasons of active growth.

There is also another kind of wood not included in the description given above, which occurs in the palm trees, bamboo, rattan, sugar cane, etc., in which the water-conducting vessels, wood fibers, and inner bark occur grouped together in small strands interspersed all through the stem with pith tissue between. The wood is not formed by concentric rings laid down circumferentially from a cambium layer, but growth takes place by an increase in the numbers of these strands. The strands are about the size of broom straws and interlace throughout the stem in the form of a network. These trees, however, are not commonly used as lumber and need not receive further consideration here. They used to be called "endogens" on account of the way in which the growth of the stem took place, and the others with concentric layers, "exogens." The endogens belong also under the angiosperms, but the seeds are monocotyledonous

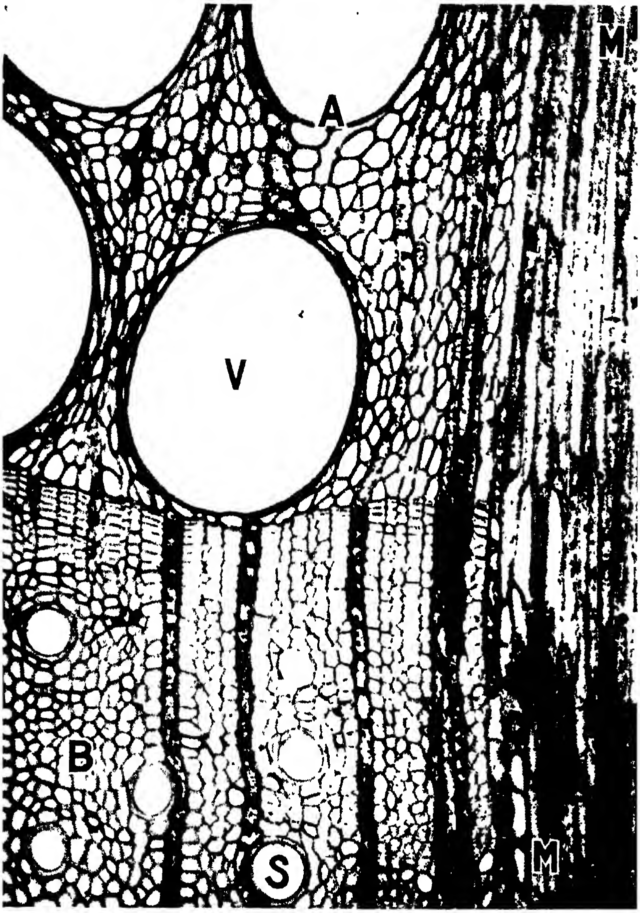


FIG. 6.—Cross section of red oak highly magnified. V, springwood vessel; S, summerwood vessel; M, M, medullary ray.

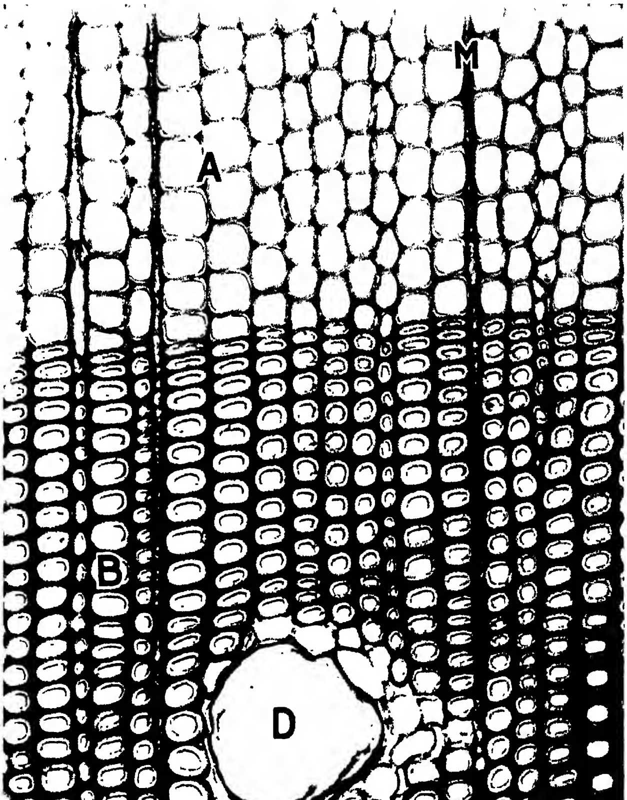


FIG. 7.—Cross section of yellow pine highly magnified. A, springwood tracheids; B, summerwood tracheids; D, resin duct; M, medullary ray.

(sprouting like corn), whereas the seeds of the exogens are dicotyledonous (sprouting like beans).

Figure 6 is the cross section of a piece of red oak showing a large vessel at V, a small one at S, dense wood fibers at B and a medullary ray MM. Figure 7 is a cross section of a piece of pine magnified the same amount, showing a resin duct D, summerwood tracheids B, springwood tracheids A, and medullary ray M.

All wood substance, irrespective of species, weighs about the same amount, its specific gravity being 1.56. Thus it will sink in water. The buoyancy of wood is due to its air spaces, and the lighter the wood the thinner are its cell walls. It is also probable that the strength of the wood substance itself is nearly the same in all species.

It is supposed that the cell walls are composed of minute particles almost molecular in size, and that moisture enters between these particles by molecular attraction or cohesion. As the amount of moisture increases the particles are pushed apart until their mutual attractive force counterbalances the cohesion attraction of the moisture, when they will absorb no more. This accounts for the hygroscopicity of wood and its power to absorb moisture from air which is only partly saturated. It is merely a hypothesis, as the particles are too small to be seen by any micro-

scope. In this respect wood is a colloidal substance. The shape and arrangement of these hypothetical particles may account for the way in which wood swells differently in different directions.

Chemically wood substance is exceedingly complex and has never been completely determined. It is basically the same in all species, but is impregnated with different substances. The basic substance is cellulose $(C_6H_{10}O_5)_x$, and with this is combined lignin, forming what is called lignocellulose. Lignin, however, has never been isolated by itself. Cotton is pure cellulose. In the manufacture of sulphite pulp, the lignin is extracted and nearly pure cellulose is left. The proportional composition of cellulose is the same as for starch and its component relationship to sugar is seen by the equation

$$\begin{array}{ccccc} 2C_6H_{10}O_5 & + & H_2O & = & C_{12}H_{22}O_{11} \\ \text{Starch} & + & \text{water} & = & \text{sugar} \end{array}$$

The conversion which can be accomplished, however, is not quite so simple as the above equation might seem to indicate.

In addition to the wall substance, wood may contain within the cells, gums, resins, combined acids, starches, volatile and essential oils, and very little albuminoids. The sapwood, particularly, is rich in gums, starches, and sugars. There are also traces of many very complex organic compounds present in most

TABLE II.—MINERAL CONTENT IN 1000 PARTS BY WEIGHT OF DRY WOOD SUBSTANCE[1]

Species	Total clean ash	K_2O	Na_2O	CaO	MgO	Fe_2O_3	Mn_3O_4	H_2PO_4	H_2SO_4	H_2SiO_4	Al_2O_3
80-year larch:											
Heartwood	1.77	.21	.023	.800	.220	.060	....	.093	.039	.343	....
Sapwood	2.70	.71	.027	.770	.293	.164	....	.341	.121	.277	....
45-year larch:											
Heartwood	.98	.12	.026	.483	.132	.047	....	.036	.024	.107	.002
Sapwood	2.29	.65	.050	.895	.182	.095	....	.276	.025	.113	.008
66-year white pine wood	1.04	.27	.028	.309	.163	.050	.026	.052	.046	.093	....
40-year aspen wood	4.18	2.01	.066	.968	.558	.044	.161	.166	.28	.080	....
150-year old red beech[2]	3.63	1.08	.12	1.11	.85	.02	.06	.21	.16	.02	....

[1] Das Holz der Rothbuche, by Hartig and Weber, 1888.
[2] Forstlich-Naturw. Zeitschrift, June, 1893. Aschenanalysen von Holz and Rinde, by Dr. Rudolf Weber.

woods and also mineral substances, as potash, calcium, magnesium, sulphur, phosphorus, iron, and soda.

The foregoing Table (II) gives the analyses for mineral content by Dr. Rudolf Weber and by Hartig. In using a table of this kind it must be understood that great variations in the ash and ash content occur in the same species and even in different parts of the same tree. The non-mineral elements are about the same in all woods, being in the proportions:

Carbon	49 per cent. by weight.
Oxygen	6 per cent. by weight.
Hydrogen	44 per cent. by weight.
Ash, etc.	1 per cent. by weight.

The ash content may vary from 0.3 per cent. to over 3 per cent.

CHAPTER III

Common Practices in Drying

Present practice in kiln drying varies enormously and there is no "standard" method. Even with the same species and for the same purpose all kinds and conditions are met with. Temperatures vary anywhere from 60° F. to above the boiling point, and inch lumber, from one to eight months air seasoned, is dried in from thirty-six hours to six weeks, thicker material from two to five months. As a general thing, hardwoods are dried at a much lower temperature than softwoods, and for some softwoods, notably Douglas fir and southern yellow pine, temperatures above the boiling point of water are used. Such softwoods are usually dried directly from the saw in the perfectly green condition, as speed of drying is the main object aimed at, but with hardwoods, especially with the dense, heavy species, as oak, hickory, mahogany, etc., it is usual to allow them first to air dry by open piling in the yards or sheds from a month to one or two years before placing in the dry kiln. The reason for this will be explained in Chapter IV, "How Wood Dries." Some of the softer "hardwoods" as basswood, poplar, yellow poplar, etc., are also occasionally dried directly from the saw. It is possible, however, to obtain the

best results with all species by doing away with the air drying entirely and placing the wood in the kiln directly from the saw. This can only be accomplished, however, by using a proper method of drying best suited to the species, as will be shown later on. In air drying there is little or no control over the conditions of the air, which change according to the weather, so that the drying is likely to take place too rapidly on some days and too slowly on others. The result is liable to be surface and end checking, case-hardening and honeycombing (Fig. 8). In a properly operated dry kiln, in which the conditions are all under control, these injuries may be avoided. Some species, indeed, can not be successfully air dried under ordinary conditions, as they will honeycomb (internal checking) very badly. This is true of the southern oaks, especially those white oaks containing large amounts of moisture, like the willow oak. It is also true of the blue gum or *Eucalyptus globulus.*

Another case which may be mentioned where air drying is injurious is black walnut gun stock blanks, which are cut into form while green and subsequently dried. This wood in this form will invariably end check in air drying unless the ends are coated with an impervious covering. In fact, most of the hardwoods if cut into blanks while green, if more than an inch in thickness, will seriously check in air drying. This is true of maple last blocks, for instance.

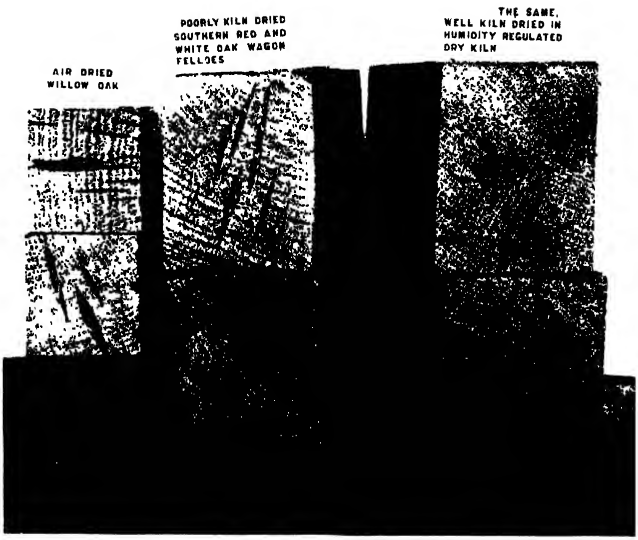


Fig. 8.—Air-dried and kiln-dried oaks, showing honeycombing. The three specimens to the left are air-dried willow oak 2X2 inches in section, the four specimens to the right are kiln-dried oak wagon felloes 3¼ inches in section, the top ones being red and the lower one white oak.

While green lumber can be better dried in the kiln if the fundamental requirements are all taken care of, preliminary air drying is unquestionably to be preferred to bad kiln drying, or where there is any doubt in the matter.

Preliminary Treatments to Drying.—Various preliminary treatments to kiln drying are sometimes used. Soaking in water is sometimes advocated, and has frequently been practised. In Japan and in Sweden it is customary to soak the wood in ponds or tanks for a year or longer before drying. Prolonged soaking leaches out soluble sugars, gums, and albumens from the sapwood, which may have a tendency to slightly reduce the hygroscopicity, but there would appear to be little if any benefit from the drying standpoint for most species, and the effect is confined chiefly to the sapwood portion of the log.[1]

A research was carried on by Gabriel Janka as to the effect upon the strength and the shrinkage of a number of species of wood produced by soaking them in soft and also in salt water. The experiment is described in full, together with tables of all the data in the reference given below.[2] These investigators conclude that the soaking in fresh water reduces the hy-

[1] See also Chapter IV, "Soaking in Water."

[2] Mitteilungen aus dem Forstlichen Versuchswesen Osterreichs, Heft xxxiii, 1907. "Einwirkung von Süss- und Salzwässern auf die Gewerblichen Eingenschaften der Hauptholzarten," by Gabriel Janka.

groscopicity and the shrinkage and also lessens the checking to some extent. It deteriorates slightly in strength.

When soaked in salt water it probably shrinks less than unsoaked wood, but chiefly on account of an increased hygroscopicity produced by the presence of the salt in the wood. It swells more when exposed to dampness than unsoaked wood, but checks less. Soaking in fresh water is recommended by this author for wood used for technical and mechanical purposes. The table on pages 27 and 28 gives a brief summary of the results as to shrinkage.

Some species of wood can be dried in the standing tree by girdling the trunk, cutting through the sap to the heartwood. This is the common practice in India with teakwood, where the trees are girdled and allowed to stand from two to three years before felling. The practice is impracticable in our present methods of lumbering, and would be detrimental in species where decay is liable to set in and borers are apt to attack the trees under the bark. In this connection it is interesting to note that the free water can be very quickly got rid of in the sapwood, if the trees are girdled or felled while in full leaf and allowed to remain until the leaves shrivel up before sawing into logs.

TABLE III.—EFFECT OF SOAKING IN FRESH AND SALT WATER UPON THE SHRINKAGE OF WOOD (AFTER JANKA).

A. Shrinkage of "pie shaped" segments cut from disks 3 cm. thick cut across the logs. The logs were soaked 1½ to 3½ years, there being 44 logs for each of the three treatments, and two disks taken from each log. The percentages given are the average of heartwood and sapwood, in the radial direction from the center to the circumference and in the tangential direction measured between the two outer corners of the "pie" or segment.

1. Shrinkage from the green or soaked to the perfectly dry condition in per cent. of the dry dimension.

Species	Moisture per cent. in the green wood in per cent of dry weight			Per cent. shrinkage					
				Radial			Tangential		
	Natural	Fresh water	Salt water	Natural	Fresh water	Salt water	Natural	Fresh water	Salt water
Spruce	114	65	81	4.45	4.45	4.20	9.38	9.52	8.97
Fir	121	89	84	3.38	3.26	3.09	8.53	8.66	8.16
White pine	115	110	73	4.13	3.01	3.09	8.96	6.92	7.50
Larch	58	72	58	5.12	4.12	4.74	10.89	8.54	9.40
Red beech	76	64	63	6.09	5.86	5.70	12.96	12.27	11.91
Oak	67	84	69	4.33	4.25	4.72	9.42	7.87	9 03
Elm	68	89	70	4.58	5.25	4.91	9.49	9.74	9.65
Maple	64	46	42	4.42	4.58	4.67	7.88	8.05	7.49
Walnut	54	91	82	5.34	4.85	5.42	6.93	7.82	7.01
Average	82	79	69	4.65	4.40	4.50	9.38	8.82	8.79

2. Shrinkage from the green to the air-dried condition in per cent of the air-dry dimensions. Air-dried three years in a room heated during winter.

Spruce	12.3	12.1	13.4	2.51	2.38	2.03	5.22	5.16	4.07
Fir	12.3	11.8	13.3	1.72	1.66	1.34	4.54	4.55	3.53
White pine	12.6	11.9	12.7	2.37	1.71	1.52	5.16	3.75	3.67
Larch	12.5	12.0	12.9	2.78	2.34	2.37	6.02	4.61	4.26
Red beech	12.0	11.6	12.9	3.70	3.37	2.97	8.76	7.82	7 01
Oak	12.4	11.8	12.1	2.35	2.62	2.72	6.07	5.13	5.45
Elm	10.9	11.0	11.9	2.70	3.05	2.55	6.10	6.13	5.07
Maple	12.0	11.4	12.8	2.42	2.50	2.10	4.56	4.85	3.87
Walnut	11.5	12.6	12.2	3.50	2.84	3.18	4.49	4.55	4.03
Average	12.0	11.8	12.7	2.67	2.50	2.31	5.66	5.17	4.55

B. **Shrinkage of saw lumber from the green to the air-dry condition.** D is a dimension timber 4 inches (10 cm.) thick cut diametrically across the center of the log, including the center. E is a board 3 centimeters thick cut 8 centimeters from the center of the log, including heart and sapwood. They were flat piled in the open under a roof and seasoned for 1 year. The moisture content varies from 16 to 20 per cent.

The shrinkage in width is given in per cent. of the green dimensions.

Species	D Timber "Quarter sawed" across center of log 4 inches thick (10 cm.)						E Board "Flat Grain" 1 3/16 inches thick (3 cm.)					
	Natural		Soft water		Salt water		Natural		Soft water		Salt water	
	Heart	Sap	Heart	Sap	Heart	Sap[1]	Heart	Sap	Heart	Sap	Heart	Sap[1]
Spruce	1.00	1.42	1.10	1.11	0.80	0.23	3.12	2.70	2.39	2.57	1.93	1.28
Fir	0.61	0.95	0.73	0.72	0.62	0.31	2.99	2.73	2.66	2.43	1.69	1.06
White pine	1.36	1.09	1.23	0.94	1.26	0.36	1.93	2.76	2.09	2.87	2.54	1.62
Larch	1.29	2.16	1.20	1.67	1.26	0.74	3.67	4.11	3.70	2.72	3.34	1.29
Red beech	1.95	1.54	2.22	1.25	1.27	0.67	5.54	4.92	5.59	4.02	3.76	2.49
Oak	1.16	0.29	1.11	1.15	1.18	0.52	5.02	3.14	3.37	2.86	3.92	1.46
Elm	2.07*	1.72	3.09*	0.88	1.28	0.28	2.96	3.51	4.77	3.00	2.28	2.79
Maple	1.66	1.56	0.77	0.89	0.89	0.31	4.88	2.92	3.63	2.37	2.24	1.88
Walnut	1.47	1.38	1.51	1.22	0.68	0.00	2.76	2.81	3.02	2.89	2.86	2.13
Average	1.40	1.35	1.44	1.09	1.03	0.38	3.65	3.29	3.47	2.86	2.74	1.78

[1] The great reduction in shrinkage of the sapwood is due to the excessive amount of salt absorbed, and consequent high moisture content or hygroscopicity.

*Influenced by checks.

Preliminary treatments of steaming both below the boiling point and under pressures as high as 20 or even 40 pounds gauge are in use at the present time. The claim is made for the pressure treatment that the subsequent rate of drying is greatly increased thereby and shrinkage is reduced. The treatment is made in a tight cylinder where the wood is given the steam bath usually for twenty minutes at twenty pounds, but sometimes for an hour or more, according to thickness. This heats the wood through to the center, and when it is brought out into the air the specific heat contained within the wood and water is capable of evaporating spontaneously a certain amount of moisture as the lumber cools to the atmospheric condition. If the wood is very "sappy," that is, if it contains considerably over 25 per cent. of its dry weight in water, the expansion of the air in the cells mechanically forces out some of the free water or "sap." Beyond this initial evaporation and expulsion of free water experiment does not show that any advantage is gained by this treatment in the drying. It does have a chemical effect upon the wood and darkens its color, particularly of the sapwood. This is of advantage in such woods as black walnut and red gum and mahogany. It reduces the strength and also the hygroscopicity of the wood, as will be shown in Chapter XI.

CLASSIFICATION OF METHODS OF DRYING AND TYPES OF KILNS

By the term "Dry Kiln" alone nothing more is conveyed than some kind of a room in which lumber may be placed and heat applied. A classification according to the shape and construction of the buildings or apparatus would be little better than a classification of ice boxes by their shape and color. There are at least twenty-five different makes on the market, and many of these embrace various kinds and sizes. A more logical way will be to classify them all according to the fundamental principles upon which they operate, or the *process* of drying.

In the first place, we will consider those which are designed for drying lumber at the normal atmospheric pressure. These consist of a chamber or room, usually from 8 to 22 feet in width and 10 to 14 feet in height, of any required length, into which the lumber may be piled, or run in on trucks or bunks which run on rails. They are built of wood, brick, cement, plaster, hollow tile, or even sheet iron—in fact, of any construction material. There are two general forms in which they are built, depending upon the manner in which it is desired to handle the lumber, namely, in the form of a long chamber or hallway, usually from 60 to 150 feet long, having rails running the entire length, and doors at either end. The trucks of lumber are run into one end, moved along periodically, and taken out at the

other end. The end at which the lumber is shoved in is known as the "wet" or green end and the other as the "dry" end. This is called a "*progressive*" form of kiln. The other kind consists of a suitable chamber, of the same cross sectional dimensions as the "progressive" but usually much shorter in length, from 18 to 70 feet, and with a door at one end only. This form is called a "charge" or "compartment" kiln. In it the lumber is placed and remains stationary until dry, the conditions of the air being changed accordingly, instead of moving the lumber along to successively drier portions of the kiln as in the progressive form. The relative merits of the two forms will be discussed further on.

Either form of kiln may be used with any of the processes. Preliminary steaming may be used with any one, and this is accomplished sometimes in a separate steaming chamber, or cylinder, or in the kiln itself; if in a progressive kiln an end compartment is curtained off for the purpose, but if it is done in a compartment form the whole kiln is used for the steaming.

A perusal of the records of the United States Patent Office shows that over a hundred different forms of dry kilns for drying lumber have been patented, as well as many of the accessories, such as doors, heating apparatus, trucks, loaders, etc. One of the earliest

ones was taken out in 1862 and is operated primarily upon the principle of a hot-air furnace. In addition to the hundred or more stationary forms of kilns for drying lumber at atmospheric pressure, there are numerous patents for apparatus in which pressure and vacuum may be obtained and in which the apparatus is mechanically revolved or moved to secure thorough heating of the entire pile of wood or other hygroscopic material which is to be dried. Evidently, many of these have failed to produce the results anticipated or have been impractical from a commercial standpoint, since there are to-day only about twenty-five kinds in commercial use.

Other Kinds of Driers.—While this publication will concern itself primarily with the subject of lumber driers, mention should be made of apparatus for drying other materials. Where the wood is sufficiently thin, namely, quarter inch or less, it is usually dried in a totally different kind of apparatus, called a veneer drier. A typical form of this apparatus is shown in Figure 9. It consists of a long flue or box, about 50 to 100 feet long by 8 feet high and 6 to 13 feet wide. Through this flue is carried horizontally on rollers a series of steel belts composed of short, narrow, flat links hinged together lattice fashion so as to allow of slight lateral motion, and to present a perfectly flat surface. The thin wood or veneer is fed into the

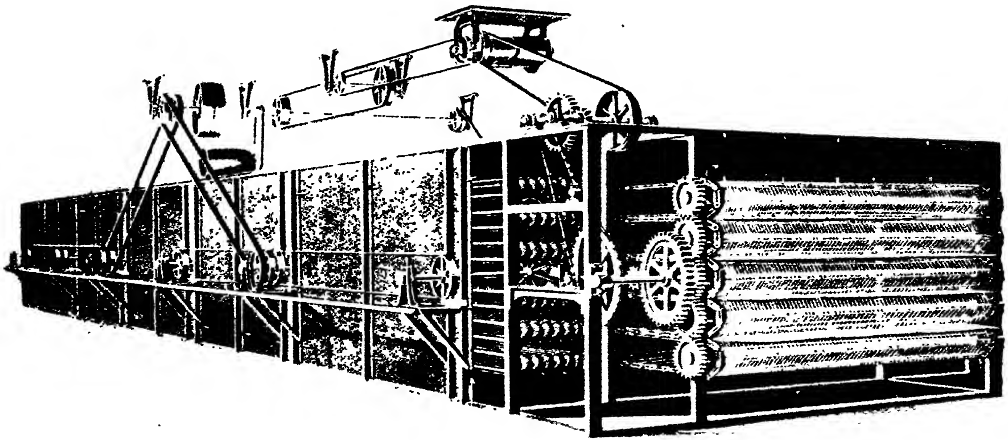


FIG. 9.—Progressive veneer drier. (Courtesy Philadelphia Textile Machinery Co.)

Fig. 10.—Heated plate veneer drier (Courtesy Merritt Mfg Co)

machine at one end between two of these belts which press upon it and hold it perfectly flat as it is carried along through the flue by the motion of the belts. The lateral play of the steel links permits the veneer to shrink without imposing stresses upon it which would cause it to check. Heated air is forced through the flue across the veneer by a series of large fans and in a direction opposite to the motion of the belts, and high temperatures are used, frequently above the boiling point, since there is not the danger of injuring this thin material that there is in the case of lumber. The time of drying will depend upon the thickness and kind of material. Thin oak veneer may be run through this machine in twenty minutes and comes out flat and dry at the other end; one-thirtieth inch sliced mahogany may be dried in four minutes, one-twentieth inch in fourteen minutes, or one-eighth inch in about sixty minutes.

Another form of veneer drier consists of a series of flat parallel iron plates, heated internally by steam, and arranged so as to open and close automatically and periodically like an accordion (see Fig. 10). The veneer to be dried is slipped in between these plates, which alternately close tight upon it, thus heating it through, then open up and permit it to dry partially, when they again close and repeat the operation until the veneer is dry.

Another kind of drier very similar to the lumber kiln is the varnish drier. This usually consists of a rectangular room, sometimes made simply of canvas stretched on wooden frames, of any suitable size, in which the freshly varnished furniture is placed, and a low heat maintained with a good circulation of air. It is important to retain a considerable amount of humidity so that the varnish will dry smoothly without crackling and to prevent the wood from shrinking. These varnish driers are usually placed inside of the shop or building, and are built dust proof. Sometimes steam pipes for heating are placed on the sides and condensers on the ceiling, or the heating pipes may be placed beneath the floor and condensers on the sides, or ventilation may be used instead of the condensers. A temperature of 110° to 115° Fahrenheit and an initial humidity of 70 per cent. gradually reduced to 30 per cent. are recommended for drying varnish on wood. Varnish on metals may be dried at higher temperature, 130°. A good circulation of air is required.

Other forms of driers are used for drying loose, granular or pulverized material, as grain, hops, powders, etc. These require mechanical stirring in order to break up the mass into which they settle and dry all portions. Some form of rotary drum is generally used.

Evaporators, for evaporating solutions, are still another form of drier. Condensed milk is produced

by evaporating the milk from shallow trays or pans in which a high vacuum is maintained so as to reduce the temperature of the boiling point. This subject has been extensively studied and books have been published which discuss it in full.[3]

Still other kinds of kilns requiring special construction are brick kilns and pottery kilns, but except for the fact that the underlying principles of their drying operations are somewhat analogous, it is hardly necessary to discuss them here.

Classification of Lumber Drying Kilns.—Returning to this subject of the drying of lumber, the kilns which operate at atmospheric pressure may be classified according to the method of operation as follows:

1. Dry air or furnace (obsolete, except for small pieces).
2. Moist air:
   - (*a*) External circulation, partly returned:
     - (1) Ventilated.
     - (2) Forced draught or blower.
   - (*b*) Internal circulation:
     - (1) Condensing.
     - (2) Humidity regulated water spray.
     - (3) Humidity regulated steam spray.
   - (*c*) Oven or boiling.

[3] See "Evaporating, Condensing, and Cooling Apparatus," by E. Hausbrand, 1908, Scott Greenwood & Sons.

3. Superheated steam:
   (*a*) High superheat forced draught.
   (*b*) Low superheat, high velocity internal circulation.

The earliest kilns for drying lumber by the use of heat were probably developed in Europe and consisted of little else than a room in which a wood fire was built in such a way that the smoke and heated gases were made to pass through the material to be dried. The smoke had the added effect of darkening the wood and was supposed also to harden poplar and soft-textured woods. The earliest kilns used in this country were of a similar pattern, or instead of the gases of combustion being used directly furnaces were used to heat the air in the kiln, and fresh air was admitted from the outside.[4]

These furnace or dry air kilns are now obsolete in this country, although they are still used to some extent in France. It is noteworthy that in the early days the idea of drying wood by heat was thought of mainly in connection with shipbuilding, where heat was already in use for bending the wood.

The present idea of "artificially" drying wood extensively by means of dry kilns is of quite recent origin, dating back not much beyond the sixties. It is noteworthy, furthermore, that the United States is far

[4] See "Timber," by Paul Charpentier, Scott Greenwood & Sons.

ahead of all other countries in the development of this art. This is, no doubt, due to the economic conditions, the excessively rapid exploitation of the forests, the enormous consumption of wood per capita in the rapid settlement and development of the new country, amounting to seven times that of Germany and nineteen times that of England, and to the necessity of reducing freight rates on shipments.

Where wood is of high value and where no great rush was made in marketing the sawed lumber, great care was used in handling and in drying. Time was not so important a factor and the lumber could well be left in closed sheds to season gradually for two and even five or more years. Sometimes durable species, as oak and teak, were buried in earth or dung to cause them to season very slowly. But where such an enormous quantity of cheap building and construction material was called for on short notice, as in the rapid reconstruction period after the Civil War, and in the vast development of the unsettled western territories by the " '49-ers," artificial drying by means of heat was the natural outcome, and having once seen the advantages of the process we have kept it up and improved it. The practice has indeed become an *art* and one which, nevertheless, when properly applied has truly many decided advantages over the old air seasoning methods. The contrast between the system used in a

gigantic American lumber producing plant and the painstaking methods at a German sawmill, where the boards from each log are carefully piled separately in the exact manner in which they were sawed from the log, is very striking.

The modern development in kilns has been away from the dry air evaporation methods and towards the retaining of more or less moisture in the air or of adding moisture to the air before it comes in contact with the wood. The term "moist air kiln" is commonly used to convey this idea. Practically all of the recent patents are for some form of "moist air kiln," or for superheated steam methods. The moisture is usually obtained from the evaporation of the lumber itself, the air being entirely or partially recirculated instead of being all discharged outwardly. Sometimes moisture is added by allowing free steam to escape in the air or by bringing it in contact with a surface or a spray of hot water.

These kilns may be divided into two groups, according to whether the air is recirculated entirely within the kiln itself, the kiln being closed to the outer atmosphere, or whether the air is drawn out or allowed to escape from the kiln and fresh air is admitted. The latter class of kilns may be termed "*Ventilated*" kilns, or "blower" kilns, according to the system used in the air motion. The moist air is secured either by per-

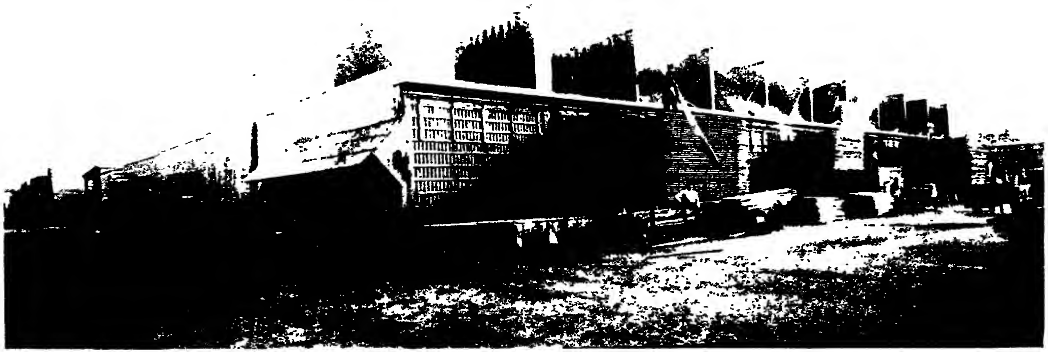


FIG. 11.—Typical progressive ventilated type of kiln. (Courtesy M. B. Farrin Lumber Co.)

forated steam pipes in the drying chamber or in the inlet flue, or from the evaporation of the lumber itself, in which case a portion of the air is recirculated. In some makes the humidity is supplied by passing the air over a tray of water which may be heated more or less, according to the humidity desired, by means of a submerged steam pipe.

Ventilated Kilns.—A well-known make of ventilated kiln of the progressive form is shown in Fig. 11. In this type fresh air enters at the dry end beneath the heating pipes through flues which extend about one-third the length of the chamber with openings on the upper side every little ways. The dry air, after rising through the heating pipes, passes through the piles of lumber in a horizontal direction towards the far end of the kiln. In taking up moisture from the lumber it becomes cooler and heavier and sinks towards the floor. It is then sucked out through openings near the floor into tall chimneys at this end. Dampers in these openings regulate the draught. The green lumber is shoved into the kiln on suitable trucks at the moist end and is moved gradually towards the dry end in a direction opposite to the current of air, whence it is removed when dry, in from several days to three or four weeks, as the case may be. It is thus seen that the entering lumber comes in contact with the dampest and coolest air first and is gradually moved into drier and hotter air.

In another type of ventilated kiln the damp air is taken out through a series of openings all along the side walls or in the ceiling. The air also enters through passageways in the walls, which discharge beneath the heating pipes arranged along the bottom. In some cases the moist air is sucked out from a series of flues from *beneath* the lumber and the fresh air is admitted near the top of the kiln. This latter method is the more logical, since, as will be shown later, the natural motion of the air in passing through the wet lumber is in a downward direction. The air motion through these flues is sometimes accelerated by placing heating pipes in their vertical extensions or by steam jets used as ejectors.

It should be noted that in all of these ventilated kilns a natural *recirculation* of the air within the kiln itself, produced by the spontaneous heating and cooling by the steam pipes and by the lumber respectively, must be obtained in addition to the current of air entering and leaving the flues, as otherwise successful drying is impracticable.

Still another form should be mentioned because it is quite distinct from the others just described, and its operation is very logical. In this kiln the damp air escapes through a narrow vertical passage on the side walls, but part of the air descends through a wider passage on either side to the bottom of the kiln from

whence it enters beneath the heating pipes and then rises, due to its being heated, passes through the lumber and again descends on the sides of the kiln; only the excess vapor produced by the evaporation escapes upwards and out under the eaves of the roof, since there is no air inlet in this kiln, except what occurs through leakages. It is suitable for drying wood which requires a very moist air.

Numerous other forms of ventilated kilns exist, but it would be impracticable to describe them all here.

Forced Draught Kilns.—In the forced draught kilns (Fig. 12), the heating apparatus is usually external to the kiln proper, being placed in the air duct, but not necessarily so. Heating pipes along the floor of the drying chamber may be used as in other forms. The main feature of this type consists in a forced draught of air produced by a slight pressure by means of a fan or blower, instead of by the "natural" or gravity currents of air as in the other cases. Sometimes the air is sucked out from the kiln, making the pressure within slightly less than atmospheric, and sometimes it is forced into the kiln, in which case the pressure within is greater than the outer air. In all cases it is necessary to properly distribute the air current by means of flues suitably arranged. In order to maintain humidity a portion of the air is usually recirculated; by connecting the exhaust flue back again

to the fan a damper is so arranged that more or less outside air may be admitted to the fan as required and the moist air allowed to escape. In some cases instead of admitting fresh air to displace the moisture produced from the evaporation, a closed circuit is used and the moisture is removed by means of condensers. The main trouble in all forced draught kilns appears *to be in the difficulty of producing a uniform circulation through all portions of the lumber, without which* uniform drying cannot take place. The reason for this is because the air motion is produced by differences in pressure between any two points in the kiln instead of by differences in density due to temperature, as in so-called "natural draught" kilns. It is possible by a proper arrangement of flues and piles to combine the natural draught with the forced air movement and so obtain the advantages of both, but this has not usually been accomplished, due doubtless to lack of knowledge of the true factors influencing circulation. One type of blower kiln is shown in Fig. 12.

Internal Circulation Kilns.—Internal circulation kilns are primarily of two kinds, namely, (1) with pipe condensers, (2) with water sprays. The latter is the kind developed by the author for the United States Forest Service, which will be more fully described in Chapter VIII. There is still another kind which has been used experimentally by the Forest Service, but

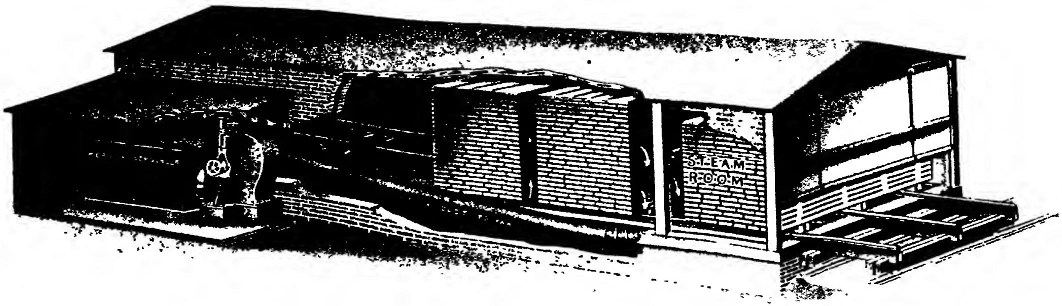


Fig. 12.—Type of forced draught dry kiln. (Courtesy of B F. Sturtevant Co.)

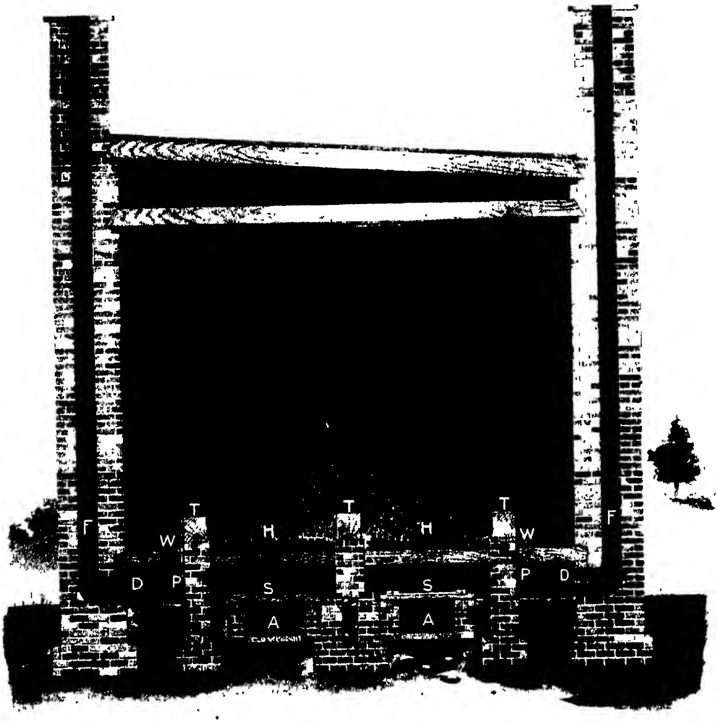


Fig. 13.—Cross section of a ventilated type of kiln. (Courtesy of American Blower Co.)

is not as yet in commercial practice. In this kiln direct sprays of live steam are used to force the circulation and they impinge directly upon water pipe condensers.

In the internal circulation kilns the motion of the air is produced wholly or in part by gravity, due to differences in density brought about by heating and cooling effects. In the spray system this "natural" circulation is greatly augmented by the force of the sprays. Where the pipe condensers alone are used the gravity effect must be wholly relied upon to produce the circulation. These kilns have the advantage over the ventilated type in that they are independent of external atmospheric conditions save for radiation through the roof and walls. The tighter they are closed the better. As a rule the compartment form of kiln is best suited for this method of drying, and is most frequently met with, although they are also used in the progressive form to some extent.

A typical form of the condensing kiln has the heating pipes located centrally beneath the lumber and the condensers on the side walls. In some kilns the condensers are placed in separate chambers on one or both sides, communicating with the drying chamber near the roof and beneath the heating coils; in others the condensers are on the side walls and shielded from the lumber by a thin partition of some kind, such as wood or asbestos board; or again the condensers may

be wholly exposed. Some makes place the condenser near the ceiling, others near the floor.

In some of the patented kilns, which do not now appear to be on the market, the condensers are placed beneath the lumber and the heating pipes on the sides. This is the most logical arrangement for green lumber, as will be seen in Chapter VI. The condensing kiln requires a considerable amount of cold water, for use in the condensers, since not only all of the moisture evaporated from the wood must be condensed and the latent heat absorbed by the water, but heat is also extracted from the air as it passes downward over the condensers. Furthermore, the pipes being almost continually wet are liable to rust very quickly. The humidity is controlled in condensing kilns by allowing more or less water to flow through the condensers. As in the case of the ventilated kilns, steam spray pipes are usually present for use where a high humidity is required.

In the water spray humidity regulated kiln, invented by the author, the water sprays take the place of the condensers. The sprays are placed in a separate chamber or flue either on the sides of the kiln or in the center, and the force of the spray water greatly increases the velocity of the air. The humidity is very simply controlled by regulating the temperature of the spray water. The sprays saturate the air and deliver

it beneath the heating pipes in a saturated condition at any required temperature. As the temperature of this saturated air is the *dew point* of the air after it passes through the heating pipes, this may be termed the "dew-point method" of controlling the humidity. The temperature of the spray water may be regulated automatically. As this kiln will be fully described in another chapter further description need not be given here.

The steam spray internal circulation method is not on the market and is merely mentioned here as a possibility, having been recently designed * and experimented with by the United States Forest Service. Steam is admitted through small perforations (about three thirty-seconds of an inch in diameter, spaced twelve inches apart) in a steam pipe in such a way that the force of the escaping steam shall add to the natural circulation of the air. In order to keep the humidity down to the required amount it is necessary to use pipe condensers, preferably placed directly in the spray, so that the steam impinges directly upon them. Evidently by this means all of the heat of the escaping steam and a little more has to be removed by the condensing water. A high internal circulation can be obtained by this means with about twenty pounds gauge steam pressure and the humidity can be uniformly maintained by adjusting the condensers. Excellent drying results have been obtained, but the

* By J. E. Imrie.

method seems wasteful of steam and condensing water unless the large volume of hot water can be made use of.

Boiling, or Superheated Steam Kilns.—For wood which will stand the high temperature a very quick way of getting rid of the free water is to heat the lumber above the boiling point. A method used somewhat extensively on the northwest coast for drying green Douglas fir and other softwoods to the shipping weight is to close the kiln fairly tight, allowing only for the escape of vapor formed by evaporation, and to allow the temperature to rise above the boiling point. The internal circulation or convection appears to be sufficient to heat the lumber, but unless the pile is very open, the inside does not dry uniformly. Inch lumber is reduced from 32 per cent. to 10 per cent. of the dry weight in 40 to 43 hours. Sometimes live steam is used at the start of this process to saturate the air.

The ordinary ventilated type of progressive kiln with steam pipes in the bottom is used for this method by closing all the ventilators. Time of drying varies in these "oven" or "boiling" kilns from twenty-two hours to five days for inch lumber. Edge piling or very open flat piling gives the most uniform results.

Another application of the boiling principle is in the direct use of superheated steam. This is generally accomplished by forcing the superheated steam into the kiln by means of a blower. A form commonly used is one in which the steam at atmospheric pressure

is superheated by passing it around a brick oven and thence into the kiln. Since the vapor pressure of water at 212° F. is equal to the atmosphere, it follows that when the vapor is heated to 212° or above, the air becomes entirely displaced and drying occurs in vapor alone. The only drying capacity which the vapor has is the heat which it contains above 212°, since at that temperature it becomes saturated and no drying can take place. It is therefore necessary to use a high degree of temperature or else an enormous circulation to accomplish the drying of the lumber. This will be more fully discussed in Chapter IX.

Drying in Superheated Steam.—A temperature of 300° F. is in use by this method. It is the most rapid method of drying there is, but since the steam loses its superheat with exceeding rapidity, the greatest effect is upon that portion of the lumber only with which it first comes in contact, since its drying capacity entirely disappears as it cools to 212°. For this reason uneven drying is likely to result. Thus, in the case of one-inch red fir, which was dried from an average moisture content of 34 per cent. to an average of 7.5 per cent. in twenty-three hours, a variation from 2 to 18 per cent. occurred in boards sampled from different portions of the pile, with flat piling. As the lumber becomes dry, its temperature will rise to that of the steam, so there is danger of injury to the wood.

High Velocity Low Superheat Method.—An im-

provement on the blower method has been developed by the author and his co-workers, Mr. Norman Betts * and Mr. James Imrie, for the Forest Service, in which a high velocity of superheated vapor is produced within the kiln itself by means of steam jets and heating pipes suitably arranged. Since the drying capacity of water vapor is directly proportional to the product of the number of degrees of superheat above 212° F. by the quantity circulated, it has been found possible to greatly reduce the temperature by thus increasing the velocity, without decreasing the drying effect. While this process has not yet been put into commercial operation, it has been proved applicable on a commercial scale through experiments recently concluded in the South on southern pines. Green inch lumber has been dried in full-sized kilns to shipping weight in 24 hours by this method. The sapwood of southern pines is darkened, otherwise the lumber comes out in perfect condition. A recent improvement in this method,[5] for use with flat piling, is shown in Fig. 14, in which the steam jets are so placed that the circulation is readily reversed in direction. It has been demonstrated to be successful on a commercial scale. It should prove particularly useful for some of the West Coast lumber, as Douglas fir,

* With deep sorrow, his death by lightning, since the above was written, is announced. Mr. Betts was a young man of marked ability and an unusually pleasing personality.

[5] Patent applied for, Serial No. 140,972, Feb. 20, 1917.

white fir, red fir, Sitka spruce, Alaska cedar, and other firs and spruces, and incense cedar.

In experiments made at the Forest Products Laboratory in Madison, Wis., incense cedar was dried from a weight of 6079 pounds per M feet to 1982 pounds in

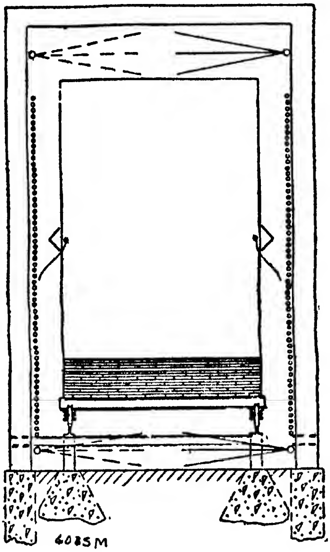


Fig. 14.—Flat piling.

48 hours, or an average rate of 83 pounds per M board feet per hour, by far the most rapid drying of which there is any authentic record for a pile of lumber of a semi-commercial size. The following species of wood have been successfully dried by this method. The time of drying, reduction in weight, and percentage of degrade are also given in Table IV.

TABLE IV.—DRYING BY THE HIGH VELOCITY SUPERHEATED STEAM METHOD

Per cent degrade	Thickness, inch	Time of drying, hours	Moisture per cents of dry weight: Dried From	Moisture: Dried To	Moisture: Rate drying per hour	Weight per M, lbs.: Dried From	Weight: Dried To	Weight: Rate drying per hour, lbs.	Temperature of kiln ° F.	From	Species
4 per cent. and case-hardening	5/4	43.2	95.1	6.5	2.05	3812	2082	39.1	227	Lewis Co., Wash.	Grand fir (*Abies grandis*).
½ of 1 per cent	5/4	48	68	5	1.3	3284	2052	25.4	225	Lewis Co., Wash.	Grand fir (*Abies grandis*).
None........	5/4	48	31	5	0 54	3140	2517	12.9	225	Lane Co., Ore....	Douglas fir (*Pseudotsuga*).
Knots loosened	10/4	96	32	8	0 2	3164	2589	4.8	225	Lane Co., Ore....	Douglas fir (mostly heart).
None.........	4/4	48	32	11	0.45	3161	2661	10.8	225	Everett, Wash...	Douglas fir.
None.........	8/4	48	30	14	0.33	3116	2733	7.9	227	Everett, Wash...	Douglas fir.
½ of 1 per cent	4/4	48	40	6	0.7	2621	1984	13.1.	227	McCloud, Cal....	Red fir (*Abies magnifica*).
½ of 1 per cent.	8/4	48	37	15	0.45	2565	2153	8.4	227	McCloud, Cal....	Red fir (*Abies magnifica*).
None........	4/4	48	81	9	1 5	3294	1984	27.3	227	McCloud, Cal....	White fir (*Abies concolor*).
None.........	8/4	48	52	23	0.6	2766	2238	10.9	227	McCloud, Cal....	White fir (*Abies con olor*).
None.........	5/4	48	59	5	1.1	2983	1982	20.8	225	Lane Co., Ore....	Yellow cypress (*Chamæcyparis nootkatensis*).
None.........	5/4	48	222	5	4.5	6079	1982	85.8	225	Lane Co., Ore....	Incense cedar (*Libocedrus decurrens*).
¼ of 1 per cent. and brown stain	4/4	48	126	19	2.2	4330	2228	41.1	227	McCloud, Cal....	Sugar pine (*Pinus lambertiana*)
¼ of 1 per cent. and brown stain	8/4	48	110	55	1.5	3931	2902	28.1	225	McCloud, Cal....	Sugar pine (*Pinus lambertiana*)
2 per cent.....	4/4	30	47	10	1 2	2836	2122	23.1	228	Missoula Co., Mont.	Western yellow pine (*Pinus ponderosa*).
4 per cent....	4/4	51	110	6	2 3	3931	2045	44.4	228	Plumas Co , Cal..	Jeffrey pine (*Pinus jeffreyi*).
3 per cent	4/4	48	125	12	2.4	6178	3075	65 9	227	Bogalusa, La.....	Longleaf pine (sap-wood).
3 per cent	4/4	48	43	7	0.75	3927	2938	20.6	227	Bogalusa, La.....	Longleaf pine (heart-wood).
Slight........	10/4	96	45	7	0 4	3982	2938	11.0	225	Bogalusa, La.....	Longleaf pine (sap and heart).

It should be noted that superheated steam methods are not suitable to the majority of hardwoods nor to many of the softwoods, and are suitable only for drying green lumber to shipping condition where the quickest possible method is called for. For high quality woods the darkening effect and the weakening of the fiber, which generally result even where there is no injury in checking, or loosening of knots which often takes place, are apt to be objectionable features.

Estimate of Saving by Kiln Drying.—The following example is given in order to illustrate how the kiln drying of wood may prove financially profitable, aside from the question of the necessity of having kiln dry wood or of the saving in losses such as checking, rotting, staining, warping, etc., which can be accomplished by proper methods of kiln drying.

The exact figures will, of course, vary greatly with local conditions, so that in giving this example it must be understood that widely different results will be found for each individual case, but the various items can be adjusted accordingly to fit the local conditions.

Assume a plant built for continuous operation for an indefinite time and handling on the average of 100,000 board feet per day of hardwood lumber, such as oak, chestnut, gum, etc., or 250 days in the year equivalent to 25,000,000 feet per year.

For air drying one-inch lumber to shipping weight will require approximately nine months, to a moisture

condition of 18 per cent. of the dry weight. To thoroughly air dry would require from twelve to eighteen months. This material can be kiln dried to 6 per cent. moisture from the saw as an average in approximately three weeks. Saving of time at least eight months. To keep eight months' supply on hand requires a yard capacity for storing $240 \times 100{,}000$ or 24,000,000 board feet. To kiln dry 100,000 feet per day will require twenty trucks each of 5000 feet capacity per day. This will require a kiln capacity of $21 \times 20 = 420$ trucks, each load being about $8 \times 8 \times 16$ feet in size. Compartment kilns end piling 12 feet wide, 12 feet high, 64 feet long, would hold four trucks each, requiring 105 kilns. Progressive kiln cross piling twenty-one trucks per kiln 20 feet wide, 12 feet high, and 168 feet long, requiring twenty kilns. The latter, if built of masonry with equipment, would cost about $140,000, the former about $210,000.

AIR DRYING COSTS (ANNUAL) SAVED BY KILN DRYING.

Capital tied up in 24,000,000 feet of lumber in yard at $20 per M	$480,000
Interest at 6 per cent.	28,800
Insurance and taxes at $1.50 per $100 per year	7,200
Yard expenses (from chains to cars, including sorting and grading, piling and unpiling), $1.64 per M*	41,000
Shipping weights saved ($18 - 6 = 12$), 12 per cent. of the dry weight of the lumber. Suppose average dry weight to be 2600 pounds per M, the saving is 312 pounds per M. At an average of 25 cents per 100 pounds = 78 cents per M or $25{,}000 \times 78$ per year	19,500

* From actual figures in oak and gum in Arkansas.

To carry 24 million feet in yard requires about 2400 piles, or a space of 13 acres. Skids for piles, tracks, hydrants, and general upkeep will amount, without counting rental, to an annual charge of		$2,000
Premium on lumber due to kiln drying, an average of $2 per M on 25,000 M		50,000
Annual saving by kilns over yard drying		$148,500

COSTS OF KILNS.

Investment in kilns	$140,000	
Storage sheds to hold lumber 10 days, 1,000,000 feet	8,000	
Trackage and extras	2,000	
	$150,000	
Extra boiler capacity 320 ℔ at $13.50 per ℔ = $4,320. Say with equipment	5,000	
	$155,000	
Interest at 6 per cent. Insurance and taxes at 6 per cent. Depreciation 7½ per cent. } 19½ per cent. on $155,000		$30,225
Handling lumber:[7]		
Chain to kiln truck	$0.12	
Loading in kiln truck	.40	
Unload and pile	.50	
Pile to R. R. car	.50	
Sorting and grading	.15	
	$1.67	
25,000 M per year at $1.67		41,750
		$71,975
Cost of operation of kilns, attendance, water, etc. Estimate		12,500
Total annual costs		$84,475
Total net annual saving due to kilns, $148,500 less $84,475		$64,025
Or a net annual saving of $2.56 per M.		

[7] From actual figures.

Of course, if the operation is only a brief one, for three or four years, the total investment in the dry kilns would have to be depreciated in that time or down to its ultimate sales value, which would probably throw the balance over on the other side. It is unsafe to make any *general* statement as to the financial benefits to be derived from kiln drying green lumber, *but it is very often* imperative to kiln dry the air-dried lumber anyway for the purposes required, and in that case, where *some kind of a dry kiln plant* is necessary in addition *to the air drying yard, there is pretty certain to be a* considerable margin on the side of kiln drying directly from the saw sufficient to cover all costs of more expensive equipment for the green drying.

Losses in Air Drying.—The above calculations did not take into consideration the saving in the losses which commonly occur in air drying, which may be obtained by proper kiln drying methods. These losses are much greater than commonly supposed, for the reason that there is seldom kept a record of them. They vary greatly with different woods and at different places. They are greatest in hardwoods, as a rule. An estimate of a total loss of 10 per cent. in air drying on all hardwoods is probably well within safe limits, and in softwoods from 4 to 7 per cent. In some instances losses have been more carefully estimated as follows:

Red gum	16 to 30 per cent. loss.
Western larch (upper grade)	60 per cent. degrade.
Southern pine	4 per cent. loss.
Southern oak	from 10 to 30 per cent. loss.
Western white pine	from 10 to 30 per cent. loss.
Shaped hardwood blanks	from 10 to 60 per cent. loss.
Applewood for instruments	60 per cent. loss.

While it is not probable that this loss can be entirely overcome by kiln drying directly from the saw, experience and experiment have shown that it can be reduced to average less than 4 per cent., and in many cases less than 2 per cent. As there are about 4,725,000,000 board feet of hardwoods kiln dried per year, and 15,116,000,000 feet of softwoods, it might be possible to save 10 per cent. on the value of hardwoods and about 3 per cent. on the softwoods. Taking an average price of $21 for the former and $16 for the latter, this would amount to a possible annual saving of $2.10 per M for hardwoods and $0.84 per M on softwoods, or a total for the United States of $17,178,000, if dried directly from the green condition by the best dry kiln methods.

This alone, without considering the question of saving of freight rates and investment in outstanding stock calculated above, would seem to justify the use of correct dry kiln methods and the employment of technical drying experts to look after this part of the lumber manufacturing business, instead of leaving the drying operation to take care of itself or leaving it to the engine tender or the yard foreman, as is commonly done.

HEATING IN DRY KILNS

The most common means of heating the lumber is by steam pipes running lengthwise of the kiln near the floor. One-inch or inch-and-a-quarter pipe has proved the most economical for the purpose. The pipes are usually built up in two or more sections, with separate headers and valves for each. A common arrangement is for the pipes to start from a supply header at one end, and bend down through a right angle elbow at the other end into a drainage header, from which a drain leads to a steam trap or a pump. The bend of the pipe is necessary so as to allow for expansion of the individual pipes, and the vertical arm should be at least twelve inches long. An excellent joint at the bend in place of the plain elbow is to run a street elbow into a plain elbow, thus making a swivel-joint and avoiding all strains at the bend and danger of cracking the elbow.

Sometimes continuous coils of pipe are used with return bends, made up in sections, in place of the headers and multiple pipes. This is perhaps the most desirable form for flexibility and uniform heat distribution, but is a little more trouble to make. If made up in continuous coil form, the coils must be properly arranged for drainage, which is important in all heating installations.

If a steam trap is used instead of an exhaust pump,

for the heating system, it is essential to have air valves placed at all high points, wherever there is any danger of air trapping, and the trap should always be bypassed so that the coils may be blown out occasionally. It is exceedingly important with the header system that the traps be working properly at all times, otherwise parts of the system may be cold while the rest is hot.

It generally pays to use the best quality wrought iron pipe (not the trade name "wrought pipe," but wrought iron pipe), as the piping in a dry kiln is subjected to excessive rust-producing conditions, and repairs are not as a rule easy or convenient to make. The reliable dry kiln manufacturers supply an excellent grade of pipe.

A caution here is made against the use of galvanized iron pipe either for heating or condensing, as the zinc coating will not hold up in a moist air dry kiln, probably due to some action of the acid fumes from the wood. The zinc very quickly turns to a dry powder and rubs off. Plain uncoated iron lasts better than galvanized iron. The best covering for the pipes, if one is used, is a high melting asphaltum or a black baking japan.

Often two horizontal layers of pipes are used, sometimes three or four layers and often only one. In any event, the pipes should be arranged so that they are all accessible for repairs. In progressive kilns the

pipes usually start from the dry end and run only about two-thirds or four-fifths the length of the kiln. Many different arrangements of pipe are in use and a great many patents have been taken out for the piping of dry kilns. In one arrangement, the pipes are placed in vertical tiers, thus making the individual units readily accessible, but at the same time losing a little in heat efficiency. After all, it does not much matter what plan of piping is used, provided it be arranged in a convenient and systematic manner.

The quantity of pipe can not be predicted in advance, since it will vary greatly in different cases and for different classes of kiln construction and climate, as well as the arrangement of the pipes.

For low-pressure exhaust steam at least double the amount of piping is necessary for medium temperature than if boiler pressure is used in the kiln, for the radiation is nearly proportional to the difference in temperature between the steam and the surrounding air. For slow, low temperature drying, as for green oak at 110°, very few pipes are necessary, not more than sixteen for a kiln twenty feet wide by twelve feet high above the rails. For high temperature drying at 180° or above the boiling point high-pressure steam is essential. A general rule to go by for drying at 130° to 140° with steam at seven pounds pressure, or at 180° to 220° with boiler pressure, is to use one piece of one-inch pipe

for every two square feet cross section of kiln taken above the piping; in other words, one foot of inch pipe for every two cubic feet of space. Thus, for a kiln twenty feet wide and thirteen feet high above the pipes 130 one-inch pipes would be about correct. Since 2.9 lineal feet of inch pipe is equivalent to one square foot external radiating surface, the above is equivalent to a heating surface of 0.1725 square foot per cubic foot of space above the pipes. It is always safe to have ample heating surface made up in several units, as it is easier to turn off some of the heat, if necessary, than to add it if deficient.

Examples of Heating Capacities.—In certain dry kilns the following amount of heating surface gave the temperatures indicated:

A. Sixty-four concrete compartment condensing kilns in one unit 18 feet wide, 15 feet above pipes, 30 feet long, 18-inch condensing chambers on either side, 38 one-inch pipes in each kiln. Exhaust steam used two to three pounds gauge. Temperatures in kilns 80° to 110° Fahrenheit. Located in Indiana.

Lengths of inch pipe to 1 cubic foot space above pipes between partitions of condensers	0.141
Square feet of heating surface to 1 cubic foot space	0.0485

B. Two Standard hollow tile kilns, tile roof overlaid with three-inch cinder concrete slab and four-ply waterproofing 18 feet wide, 13 feet above pipes and 150

feet long. 15,150 lineal feet of inch pipe in each. Exhaust steam at three pounds gauge used. Temperature at dry end 160° F. Located in Ohio.

Length of inch pipe to cubic foot space	0.429
Square feet heating surface to cubic foot space	0.149

C. Brick compartment, condensing, with partitions on either side 17¼ feet between partitions, 13 feet above top layer of pipe 50 feet long. Steam at 7½ pounds gauge. Temperature 150° and 53 per cent. humidity; in Virginia, outside temperature being about 30° Fahrenheit.

Linear feet pipe per cubic foot space	0.361
Square feet heating surface per cubic foot space	0.124

D. Brick and concrete condensing chambers on either side, 20 feet wide between partitions, 14 feet above pipes 104 feet long; in northern Wisconsin. (Winter usually 20° below zero.)

At green end steam 5¾ pounds gauge gave 150°, 95 per cent. humidity:

Linear feet pipe per cubic foot space	0.28
Square feet heating surface per cubic foot space	0.098

At dry end, 5¾ pounds gauge, 165°, 60 per cent. humidity:

Linear feet pipe per cubic foot space	0.64
Square feet heating surface per cubic foot space	0.222

E. Four hollow tile, condensing both sides; no side partitions, 20 feet wide, 11 feet above rails, 124 feet long. Coils throttled and vacuum pump used. When full of green lumber 110° at 70 per cent. humidity.

130° and 30 per cent. humidity at dry end. In Massachusetts. (0° F. in winter.)

Lineal feet inch pipe per cubic foot space	0.585
Square foot heating surface per cubic foot space	0.202

An excellent way to regulate the heat is by means of a reducing valve on the main steam line by which any desired temperature may readily be produced by changing the steam pressure accordingly. The best results are obtained by using two reducing valves in tandem, the first one reducing into a capacity, such as a large piece of pipe, and the second reducing further to the required pressure. By thus stepping down in two stages from the boiler to the required pressure perfectly uniform pressure may be maintained. Another good method is to use a thermostat on the main steam line; but if a thermostat is used it should be of the very best make, for should it fail to operate at any time there is danger of overheating the kiln.

Calculations for Heating Capacity.—The following example will show how the heating capacity for a dry kiln may be calculated, although, as stated, there are so many variables that the result is after all little better than a guess, yet it will serve to indicate something as to possibilities.

Let us assume that 50,000 feet of one-inch yellow pine are to be dried, in four days, or at the rate of 12,500 feet per day, from an average moisture content

of 70 per cent. to shipping weight of 20 per cent., and at a temperature of the entering air of 212° Fahrenheit. Let us suppose that the air enters the steam coils in a saturated condition at 70° and leaves the kiln three-quarters saturated, 75 per cent. relative humidity. The 50,000 board feet will represent, if the lumber is fifteen-sixteenth inch thick, about 3900 cubic feet. Dry yellow pine weighs from 38 to 42 pounds per cubic foot, say 40 pounds, and since there is 50 per cent. (70—20 per cent.) water to be extracted the weight of water is 20 pounds per cubic foot, or a total weight of $3900 \times 20 = 78,000$ pounds of water to be evaporated in four days.

In considering the heat quantities involved, the radiation from the kiln walls will not be included in the consumption, because the heat remaining in the air leaving the lumber will supply this loss and need not add to the quantity consumed, since if it is not utilized in heating the kiln walls it must be lost into the outside air or consumed by the condenser. Nevertheless, there will, no doubt, be some loss of direct heat through the walls. Now to evaporate one pound of water at 212° would require one pound of steam, if it could all be utilized for this purpose, or 966 British thermal units. But this is not the case when air is present, since some heat is utilized in heating the air. The theoretical amount has been worked out in Chapter X and is given

in Table IX. Taking the nearest value to our given conditions from this table, we find that saturated air entering at 59° F. heated to 212°, and leaving 75 per cent. saturated has a leaving temperature of 103°, and that 1572 heat units are required to evaporate one pound. This value includes the heat consumed in raising the temperature of the water from 59° to 103°, which must be included. Therefore, to evaporate the 78,000 pounds will require a minimum of 122,616,000 B.t.u. in 96 hours, or 1,277,250 B.t.u. per hour. This represents 1277 pounds of steam consumption per hour (total heat of steam above 212° at 307° = 1000) or 1317 pounds at 212°. Taking a boiler horsepower as 34.5 pounds evaporated from and at 212°, it represents 38.3 boiler horsepower. This is the minimum possible amount, and it is probable that in most cases at least 50 per cent. more than this must be figured upon, or 1915.5 pounds steam per hour, or a total of 183,885 pounds of steam, or 57.3 boiler horsepower.

For a longer drying period than four days, or for less moisture in the green lumber, the steam consumption per day will be proportionately less.

For the amount of heating pipe required, several factors come in to greatly modify this, steam pressure, velocity of air passing over the pipe, and the temperature of this air; that is, whether the entire amount is

fresh cold air or whether some of the heated air in the kiln is recirculated; also the humidity of this air. In order to carry a temperature in the kiln of 212°, boiler pressure steam is necessary, because exhaust steam is not hot enough. The heat radiated from iron pipe varies for different sized diameters up to 12 inches. Nystrom[8] gives the following formula:

Heat radiated per square foot of heating surface per hour in British thermal units =

$$.001122\left\{450+(12-D)^2\right\}\times(T-t)^n$$

when

D = outside diameter of pipe.
T = temperature of steam in F. degrees.
t = temperature of air passing over pipes.
n = a numerical exponent depending upon velocity of air.

The following are the values given for n:

Calm	n = 1.20
Gentle	n = 1.22
Brisk	n = 1.24
High	n = 1.26

Assume that one-inch pipe is to be used, the area in square feet per 100 feet length is 34.5 and D is 1.315 inches. The heat radiated per 100 feet length is then

$$34.5\times.001122\left\{450+(12-1.315)^2\right\}(T-t)^n = 21.84\ (T-t)^n$$

For various sized pipes the coefficient for multiplying $(T-t)^n$ per 100 foot length is:

[8] Nystrom Pocket Book.

½	14.3
¾	17.62
1	21.84
1¼	27.36
1½	30.80
2	37.87
2½	45.06
3	55.71

For an ordinary kiln take n as 1.22. Suppose the effecting steam pressure to be 60 pounds = 307° F. = T. The entering air is 70° and it is to be heated to 212° before it leaves the steam coils, so that the air coming in contact with the pipes will be saturated and at a temperature of 70°. The equation then becomes

$$h = 21.84\ (307-70)^{1.22} = 17{,}236$$

heat units per hour per 100 feet of one-inch pipe imparted to the air. (This is equivalent to a radiating factor of 2.11 heat units per square foot per degree difference in temperature.)

The amount of heat required was found to be 1,277,-250 × 1.5 = 1,915,875 B.t.u. per hour, which divided by 17,236 gives 111.15 hundred-foot lengths of pipe, or 11,115 feet of one-inch pipe.

Let L equal the total heat above 212° contained in a pound of steam at temperature T = 1000 B.t.u., and W = weight of steam condensed per hour. Then

$$W = \frac{N}{L} = \frac{17{,}236}{1000} = 17{,}236 \text{ pounds}$$

steam condensed per hour per 100 feet length of one-inch pipe, or a total of 111.15 × 17.236 = 1915.8 pounds per hour, or 31.93 per minute.

To find the size of steam main desirable to supply 31.93 pounds of steam per minute, we must assume what drop in pressure is permissible for the given length of feed pipe. This may be calculated from Babcock's formula:

$$W = 87 \sqrt{\frac{D(P_1 - P_2)d^5}{L\left(1 + \frac{3.6}{d}\right)}}$$

Where W is the weight of steam in pounds per minute P_1 is its initial pressure and P_2 its final pressure after passing through the length of pipe L in feet. D is the weight of a cubic foot of steam at the initial pressure P_1 and d is the diameter of the pipe in inches. To simplify the calculation the following table has been worked out from this formula for a length of pipe, L, of 100 feet and a difference of pressure P_1–P_2 of one pound:

Table V.—Flow of Steam in Pounds per Minute Through a Straight Pipe 100 Feet in Length with a Reduction of Pressure of 1 Pound per Square Inch.

Gauge pressure	Nominal diameter pipe								
	1	1¼	1½	2	2½	3	4	6	8
Pounds per square inch	Actual diameter, inches								
	1.05	1.38	1.61	2.07	2.47	3.07	4.03	6.06	7.98
0	.90	1.98	3.06	6.26	10.27	18.83	39.82	120.3	253
10	1.15	2.52	3.89	7.96	13.06	23.94	50.62	153.0	321
20	1.35	2.96	4.58	9.36	15.37	28.18	59.58	180.1	378
30	1.51	3.31	5.12	10.48	17.20	31.52	66.65	201.0	423
40	1.67	3.67	5.67	11.59	19.03	34.88	73.76	222.4	468
50	1.81	3.97	6.14	12.47	20.59	37.75	79.82	240.7	506
60	1.93	4.24	6.56	13.42	22.03	40.38	85.39	258.0	542
70	2.04	4.48	6.94	14.18	23.28	42.68	90.24	272.7	573
80	2.16	4.74	7.33	14.98	24.59	45.08	95.32	288.1	605
90	2.26	4.96	7.67	15.69	25.75	47.20	99.80	301.6	633
100	2.37	5.20	8.04	16.45	26.99	49.48	104.60	316.2	664

For lengths of pipe other than 100 feet, divide the values given in the table by one-tenth of the square root of the given length. Thus, for a pipe 144 feet long divide by 1.2.

For any other difference in pressure, multiply by the square root of this difference.

The resistance due to a globe value and to the entrance of the pipe may be taken each as equal to a length of pipe in feet of $\frac{9.5d}{\left(1+\frac{3.6}{d}\right)}$ and an elbow as two-thirds of a globe valve. The added length equivalents in feet for a globe valve according to this are:

Nominal diameter of pipe	1	1¼	1½	2	2½	3	4	6	8
Equivalent length	2.35	3.6	4.7	8.7	9.6	13.4	20.2	36.0	52.0

Thus for a four-inch pipe 100 feet long having one globe valve and three elbows, the resistance is equivalent to 4 × 20.2, or an added length of 80.8 feet, or is equivalent to a straight piece of pipe 181 feet long. Thus the actual drop in pressure as compared to the unbroken pipe 100 feet long would be 1.81 pounds per square inch, for the amount of flow given in the table, or it would deliver a flow of $\frac{1}{\sqrt{1.81}} = .743$ times the values given in the table for the 100 feet unbroken pipe.

According to the calculation on page 66, 1915 pounds per hour of steam is required, or 31.9 pounds per minute. From Table V it is seen that at 60 pounds

pressure a three-inch pipe 100 feet long having one globe valve and two elbows would deliver $.743 \times 40.38$, or about 30 pounds with a drop of one pound in pressure. A three-inch pipe would, therefore, be ample if the distance is not long, but if the length is greater than 100 feet or there are more resistances, a four-inch pipe would be better.

Approximate Calculation.—The calculation may be more roughly approximated by assuming a radiation of 2.1 heat units per hour per square foot heating surface per degree difference in temperature. Let $X =$ heating surface required, for a difference $(T-t) = 237°$, then $2.1 \times X \times 237 = 1{,}915{,}875$. $X = 3849$ square feet. 2.9 lineal feet of one-inch pipe = 1 square foot heating surface. Therefore, $4491 \times 2.9 = 11{,}162$ lineal feet pipe required. This calculation all depends upon choosing the proper radiation coefficient 2.1, which may vary from 1.5 up to 3.0 according to the size, arrangement of piping, and the velocity of the air.

For low pressure steam heating the diameter of the supply pipe in inches is often taken as one-tenth the square root of the heating surface in square feet $1/10 \sqrt{3849} = 6.2$ inches.

Kiln Capacity.—The size of the kiln would depend somewhat upon its construction and method used in drying, and whether the lumber is in even lengths. Let us assume that the lumber will be flat piled with one-

inch stickers between the boards and that a ventilating type of kiln is to be used with cross piling, the lumber to be 16 feet in length. To obtain satisfactory results by this method the piles must not be too high and a space must be left between each truck and the boards spaced two or three inches apart. To allow clearance the kiln will need to be at least eighteen feet wide and at least two feet between the top of the pile and the roof. A space of about two feet will also be required below the rails and about a foot for the rails, trucks, etc. Thus the kiln must be twelve feet high for seven-foot piles of lumber. Suppose each truck is six feet in width, it will then hold approximately a pile of lumber $7 \times 6 \times 16$ feet, which if the boards were close-piled with one-inch stickers would contain $\frac{1}{2} \times 7 \times 6 \times 16$, or 336 solid cubic feet. Allowing about $\frac{1}{4}$ of this for the spaces between boards, each truck would hold 252 cubic feet on 3024 board feet. It would, therefore, require sixteen trucks to hold the 50,000 feet. Allowing a space of one foot between each truck and the ends of the kiln the length required would be 113 feet. This kiln would be operated progressively at the rate of four trucks per day. Or four compartment kilns twenty-nine feet in length and thirteen feet high by eighteen feet wide, each holding four trucks, would serve the same purpose.

Another Example.—The above example was given

for rapid drying at a high temperature. Let us take another case where the entering temperature is to be 158° F. and the humidity 63 per cent., the air being recirculated and entering the heating pipes in a saturated condition at 140°. Our choice will lie between some kind of a condensing kiln or a recirculating blower kiln. Let us suppose that green inch birch is to be dried from 60 per cent. moisture to 30 per cent. in six days, or at an average rate of 5 per cent. per day, and then further dried to 6 per cent. at a higher temperature, which will require a considerably longer time. Let us also assume 50,000 feet of inch lumber are to be handled in this length of time. Assume that the temperature of the lumber when brought into the kiln is 0° F. and the lumber is solidly frozen. For every pound of dry lumber, therefore, there will be 0.6 pound of ice to be heated from 0° to 32° and melted at 32°, then the lumber and water must be heated to 140° before any drying begins. Half of this water is then to be evaporated and this feat accomplished in six days. The heat necessary to heat the lumber and its contained water to 140° per pound of dry wood will be as follows:

(1) To heat 1 pound of dry wood from 0° to 140° = 0.33 (specific heat of wood) × 140	46.2 B.t.u.
(2) To heat 0.6 pound ice 0° to 32°, 0.6 × 0.5 (specific heat of ice) × 32	9.6 B.t.u.
(3) To melt 0.6 pound ice = 143 × 0.6	85.8 B.t.u.
(4) To heat 0.6 pound of water from 0° to 140° = 0.6 × 140	84.0 B.t.u.
Total heat required	225.6 B.t.u.

Turning to Table IX, on page 245, it is found that for air entering saturated at 140° and heated to 158°, if it leaves the lumber also saturated, the minimum possible heat required is 1119 B.t.u. per pound of water from 59°, or 1037 from 140°. To evaporate 0.3 pound from and at 140°, therefore, requires 311 B.t.u. As a matter of fact, the air will have to leave the lumber considerably less than saturated, which will require a greater heat consumption, probably at least one-fifth more, or 373. Summing up the several heat requirements, to evaporate 0.3 pound of moisture will require a minimum consumption of $226 + 373 = 599$ B.t.u., or 1997 B.t.u. per pound evaporated.

Since the outside temperature in this case is much colder than before, namely 0° F., it is probable that the radiation from the kiln walls will considerably exceed the latent heat from the evaporated moisture and it would therefore draw directly upon the heat supply. This is a factor which can not be accurately worked out, however, and there will be other losses in leakages through the doors and cracks and through the floor. But for the sake of pursuing our system of estimating let us see how it can be figured out.

The same sized kiln as before will hold the lumber, having an outside dimension of approximately $20 \times 30 \times 115$ feet. The superficial area, exclusive of floor, will be 5810 square feet. If the floor is cement

or sand and inclined to be damp it will transmit at least as much heat as the roof, so we will count it as the roof, giving a total area of 8110 square feet. The temperature in the inside may be taken as an average of 140° and 158° or 149°, the outside being 0° Fahrenheit. Turning to the table on page 96, it is found that the heat loss through a brick wall twelve inches thick is about 0.31 B.t.u. per square foot per hour per degree difference in temperature. Therefore, the loss per hour from the kiln would be $0.31 \times 149° \times 8110 = 374{,}601$ B.t.u. In six days this would total $374{,}601 \times 144 = 53{,}942{,}544$ B.t.u. Let us see now how much heat is required for the lumber. 50,000 board feet = 4167 cubic feet. In one cubic foot of green birch there are forty-three pounds of dry wood and $0.6 \times 43 = 25.8$ pounds of water, of which half is to be evaporated in six days, or 12.9 pounds per cubic foot, a total of 53,754 pounds. The latent heat at 140° F. is 1013. There should, therefore, be available for heating the kiln walls $53{,}754 \times 1013 = 54{,}452{,}802$ B.t.u., which is seen to be slightly more than the amount required. We may, therefore, neglect this factor, for a well-built brick kiln.

Now as to the total amount of heat required to heat the frozen lumber and evaporate 30 per cent. of the dry weight in water in six days. On page 71 it was shown that to accomplish this requires for each pound

of dry wood 599 B.t.u. Therefore, the total amount required is 4167 cubic feet $\times$ 43 pounds $\times$ 599 = 107,329,419 B.t.u. It will be safe, however, to increase this by 50 per cent. for leakages, making a total of 160,994,000 in round numbers, or at the rate of 1,118,015 B.t.u. per hour.

In this case low-pressure steam might be used, but it would require an excessive amount of piping. We will, therefore, assume, as in the case of the yellow pine, that steam at 60 pounds is to be used in order to avoid duplication in our calculations. In this case $h = 21.84(307-140)^{1.22} = 11{,}245$ heat units per hour per 100 feet of one-inch pipe imparted to the air. There will be required, therefore, $1{,}118{,}015 \div 11{,}245 = 99.42$ hundred-foot lengths of pipe, or 9942 linear feet of one-inch pipe. It should be observed that in all these calculations only an approximation is possible on account of the great number of variable conditions. It is always a good plan, therefore, to have an excess of heating capacity. Furthermore, the drying of the free water is assumed to take place at a uniform rate, which is not the case. It is interesting in the last example where 50,000 feet of green birch timber is to be dried in six days to its fiber saturation point, from a temperature of 0° F., that 4167 cubic feet $\times$ 25.8 pounds = 1,076,088 pounds, or over 500 tons of ice have to be melted before drying even begins!

Condensing Pipes.—The amount of condensing surface required in a kiln which is tightly closed and dependent upon the condensers for removal of the moisture is an indeterminate quantity. It depends somewhat upon the amount of moisture to be removed per hour, the temperature of the walls of the kiln, the amount of circulation of the air, the position in which they are placed, the temperature of the condensing water, the tightness of the kiln, the temperature of the drying, and how much live steam is used at the green end or during the beginning of the drying operation. It is always safe to have an excess of condensing surface, since the action can at any time be reduced as much as desired by throttling the water flow and thus increasing the temperature. Moreover, less water is required if the condenser is large than if it is too small. If the condenser is too small it is impossible to remedy the difficulty by increasing the water flow, since when the water leaves the pipes at approximately the same temperature as it enters, the limit of action has been reached, and an excessive amount of water is required.

The side walls of the kiln, if it is a separate building, the roof, and the doors act as condensers, particularly in cold weather, and greatly augment the action of the water pipes. If the temperature of any surface of the kiln is below the dew point, condensation will occur thereon and drops of water will fall from

the surface just as from a pipe condenser. The condenser should be made up in a continuous coil, or in several independent coils, and *not* with headers or distributing pipes. For a kiln twenty feet wide and fourteen feet high above the heating pipes from twelve to sixteen one-inch pipes placed on both side walls are sufficient for low-temperature operation 110° to 140°. For higher temperatures less pipes are needed. In figuring on the quantity of water necessary, the temperature of the leaving water may be taken as approximately at the *dew point* of the air within the kiln. The heat extracted must be at least twice, and it is safe to figure upon three or four times the latent heat of the water evaporated from the lumber in a given time. To explain: Suppose a small compartment kiln holding 10,000 feet of green lumber at 60 per cent. moisture. This is to be dried to 5 per cent. in fourteen days. If this is red gum at 4400 pounds per M it will weigh about 2888 pounds when dry, and the total loss of moisture will be 15,120 pounds, or, roughly, about 15,120,000 heat units. This would be 45,000 heat units per hour. Assuming a required temperature of 130° and 60 per cent. humidity during the first part of the drying, temperature of entering water 60°, its maximum leaving temperature should not exceed 112°, the required dew point (although it may be any amount lower than this). Thus the heat absorbed by the condenser

would be $112° - 60° = 52$ heat units per pound of water circulated. There are 45,000 heat units per hour in the evaporated moisture, $45{,}000 \div 52 = 862$ pounds of water. But a lot of heat is likewise extracted from the air. Taking three times this amount as suggested above gives 2586 pounds of water per hour as the minimum quantity necessary at 60° Fahrenheit. If the walls and roof are cold, a considerably less quantity than this would be needed.

In the case of the humidity regulated kiln, with water sprays on either side in place of pipe condensers, less cold water than this is required for the first part of the run, but the total amount of warm water recirculated is slightly more than this. A very much greater circulation of air is produced by the water sprays than by the condensers, however.

Do not use galvanized pipe for condensers in hardwood dry kilns, as the acid fumes will destroy the zinc coating quicker even than plain iron. Paint the pipes with a good asphaltum varnish or black baking japan.

Doors, Rails, Trucks, Fire Protection and Accessories.—Most dry kiln manufacturers supply all the apparatus necessary for a complete installation. Where rails are used these are usually supported upon cast iron or wooden posts, to which also the heating pipes are fastened. In progressive kilns, three rails

is a common practice, one in the middle and another on either side. The trucks to hold the lumber in this case are usually arranged for "cross piling"; that is, with the boards running crosswise of the kiln. Sometimes a complete platform is built up of structural steel with six wheels to run on the three rails, but more often three separate bunks are used, built up of two channel irons, four to six feet in length, with two wheels between, and the lumber is piled directly upon these bunks. This arrangement is for convenience of handling the trucks in returning them back again from the dry end of the kiln to the loading or green end. The journals of the wheels are generally lined with roller bearings to reduce friction.

Sometimes four rails are used and two trucks are run into one kiln side by side. In this case the lumber is generally "end piled," that is, with the boards placed lengthwise of the kiln, and solid four-wheeled structural steel trucks are used.

In most progressive kilns it is necessary to have the rails on an incline to facilitate the movement of the cars from the green towards the dry end. A slope of 2.5 per cent. is common. In some cases this is too steep and a slope of 1.4 per cent. or 1 inch in 6 feet is found sufficient.

There are many forms of dry kiln trucks which have been patented. Some of these are arranged for

stacking the lumber edgewise, so that the air can pass freely through the pile in a vertical direction. A difficulty with some of these is that no provision has been made for keeping a pressure on the lumber after it has begun to shrink. Recent forms of edge stacking trucks have a device such that the weight of the load of lumber itself brings a lateral pressure to bear constantly by means of auxiliary bars, thus automatically taking care of the shrinkage. There are two different forms of this apparatus where the weight of the load is utilized to produce the pressure. In yet another form the result is accomplished by means of springs and cams. These trucks are called automatic shrinkage take-up edge stacking trucks. Various systems of loading lumber on edge are in use. In one form the entire truck is pivoted horizontally and may be swung around from the horizontal to the vertical positions, and back again. In another the truck is run on to a "turn table" which is tipped by gearing so that the boards are loaded in an inclined position, and when the load is clamped fast the truck is turned back to the vertical position again when it is ready to run into the kiln. An automatical loader is also used in connection with this truck, so that the lumber is fed directly from the mill chains on to the kiln truck, without manual labor. Unless edge stacked lumber has some form of automatical shrinkage take-up it is sure to warp and

twist in drying, since even if packed very tight when placed in the kiln the pile will become loose as soon as it dries and begins to shrink.

Various other forms of holders are used for special purposes as staves for pails, small cribbed material, etc. In some cases small blocks are dumped on to the kiln floor, hopper fashion, in loose piles.

In many kilns, particularly in those of the compartment form, no trucks are used, the wood to be dried being piled by hand directly in the kiln.

The door of a dry kiln is an important consideration, and often badly neglected. Unless the door is easily operated, fits air-tight and is a good insulator, satisfactory results can not be expected of the kiln. A tumbledown door means lost heat and many a lost temper, as well as waste labor and inability to maintain uniform moist conditions within the kiln.

Doors are constructed of wood, of asbestos with wood frame, or of canvas. The wooden or the asbestos doors are made to slide horizontally as a barn door, to lift up, like a stage curtain, and sometimes to fold outwardly. One of the very best dry kiln doors slides horizontally and is operated by a separate sling frame device, which latter runs on a horizontal track above the door. This device is moved over the door, and by the motion of a single lever the door is clamped, lifted off of its sockets, and swung free (Fig. 15). It may

then be shoved to one side. It is replaced in the same manner and as the lever is released the door drops down into its sockets, which are inclined so as to force the door tightly against its sills by its own weight. This apparatus is patented and known as the Hussey Dry Kiln Door Carrier. The doors may be made of wood or built up of asbestos framed in wooden lattice.

Another form of door which gives excellent service consists of a double canvas curtain with an air space between of about one foot. It is, in fact, two entirely separate curtains which are rolled up by means of ropes and are so arranged that when they are let down the edges may be tightly clamped against their sills by means of boards. The main objection to canvas is its lack of durability (Fig. 15*a*).

There is also an articulated steel curtain door, such as is used in warehouses. While it has the advantage of being fireproof and durable, it has a great disadvantage in its heat conductivity. It is not generally used.

Forms of Piling.—Probably the commonest form in which lumber is arranged for kiln drying is by "flat piling," the boards or planks being laid in horizontal layers. Small strips of wood are laid between the layers running at right angles to the boards, usually these "stickers" are planed to even thickness of about three-fourths to one inch for inch lumber and one and

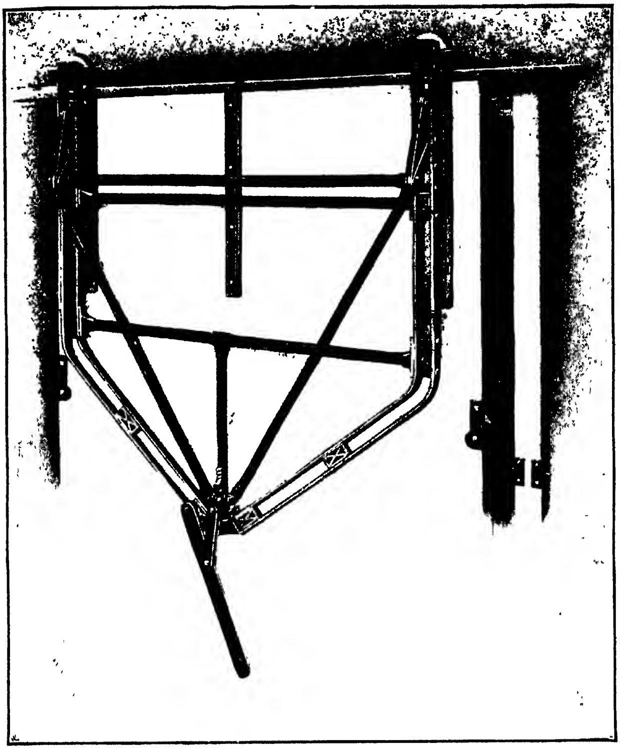
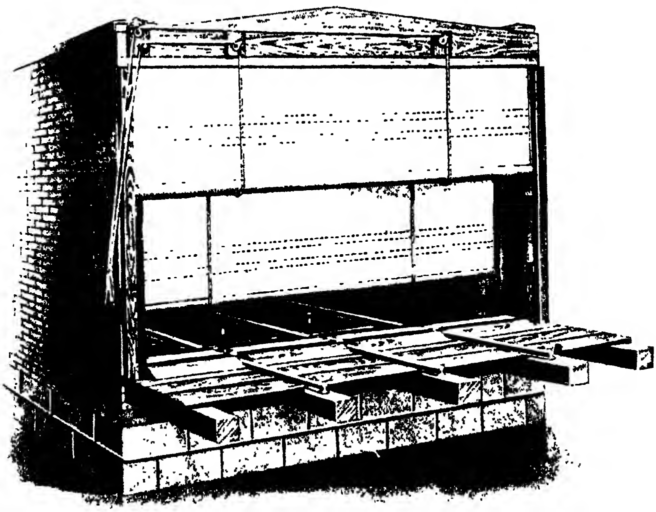


FIG. 15.—Hussey door carrier (Courtesy of National Dry Kiln Co.)



a half to two inches for two-inch planks. The distance they are spaced apart depends upon the kind of lumber, and the method of piling. For pine lumber they are spaced from four to six feet apart, but for hardwoods, especially woods inclined to warp, they are placed every three feet or even every eighteen inches. The stickers should be narrow, so as to cover as little surface as possible. They are commonly made square, though sometimes they are two or three inches wide. The use of narrow boards placed crosswise of the pile, for stickers, such as is often done in air drying, is bad practice for kiln drying and is not usual, since they cover up too large an area of the boards. The stickers should be dry, and not rotten or stained, nor of a wood likely to discolor the boards. Pine, fir, Douglas fir, and spruce are excellent woods for stickers. In flat piling it is usual to leave a space of at least an inch between adjacent boards. Sometimes the boards are staggered, that is, placed so that boards and spaces come alternately one above the other, and sometimes the spaces are arranged to come vertically above one another so that they form vertical chimneys in the piles. Sometimes the piles are arranged so as to have one to three or more vertical chimneys half a foot to a foot in width extending the height of the pile or only half the height. Again, tent-shaped openings are left in the center of the piles.

A common height of pile is from eight to tw feet; the length depends upon the length of the lum and the width may vary from four to six feet. If boards are placed in the pile so as to run crosswise the kiln, the method is known as "*cross piling*" when they run lengthwise of the kiln the term "*e piling*" is used. As a rule cross piling is used in pr gressive kilns and end piling in compartment kiln A common amount to be placed on a single truck from 3000 to 4500 board feet, but it may be almost an amount.

There is, in fact, as little uniformity in methods o piling as in methods of drying. The best methods to use in various types of kilns will be discussed in Chapter VI on the "Circulation in Dry Kilns."

Another form of piling is with the boards placed edgewise, the stickers running vertically. In this system the boards touch one another, edge to edge. It requires a specially designed truck to hold the lumber, and unless this is arranged to bring a continual lateral pressure upon the lumber, it is sure to warp as it shrinks. Three or four designs of automatic shrinkage take-up trucks have been patented and are occasionally used. Though this method of piling is seldom met with, its use appears to be increasing in favor, especially for Douglas fir and longleaf pine. Special stacking machines are generally used where edge stacking is practised.

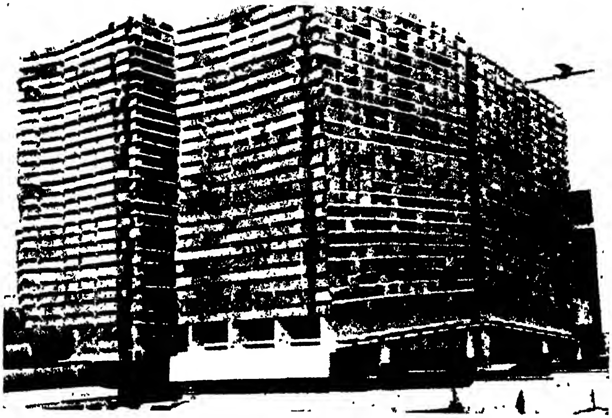


FIG 16.—Black walnut gun stock blanks arranged with inclined piling for kiln drying in the Tiemann Humidity Regulated Kiln The car contains about 11,000 blanks. Note central flue.

FIG. 17.—The disastrous effect of improper methods of kiln drying black walnut gun stock blanks.

Another form of piling, which has been used with great success in the author's Water Spray type of kiln, is *inclined piling* (Fig. 44). Here the lumber is sloped crosswise of the pile, the stickers being inclined, the boards being horizontal as regards the length of the pile. The arrangement is such that the air is made to pass through the pile in the *downward* direction, as it is cooled by the evaporation and becomes denser in passing through the pile. The slope of the pile depends upon convenience, but should be as great as possible for the best effects: a slope of one foot in seven gives a good draught. This form of pile requires no special machinery and may be easily handled as a flat pile. The piles should be kept as narrow as possible, not over four feet wide for best results, and the boards may be placed so as to touch one another edge to edge.

Formed material, such as gun stock blanks, may be arranged to advantage in sloped piles of this kind. Figure 16 shows such a pile about sixteen feet wide and eight feet high containing about 11,000 black walnut green wood gun stock blanks. The open spaces, between adjacent blanks, due to the uneven contour of the material, amounting to about two and a half inches at the widest part, still further facilitates the circulation, allowing the air to move downwardly in a diagonal direction through the pile. The blanks are two and

a half inches thick, and about one-inch stickers are used.

Shingles are usually bundled, and the bundles stood flatwise or edgewise on the trucks, thus leaving many horizontal or vertical flues through the piles. Cooperage staves are arranged in a somewhat similar manner, or are piled in the kiln on end. Smaller staves for pales are sometimes cribbed. Laths are bundled and the bundles laid horizontally on trucks. Shoe lasts and smaller material are usually cribbed.

End Coating.—Except with the very valuable woods it is not the usual practice to paint the ends of lumber placed in the dry kiln, chiefly on account of the expense. Where the lumber is sorted into even lengths a good practice is to have the end stickers come flush with the ends of the boards. As wood dries twenty to thirty times as rapidly endwise as it does across the grain, it is always desirable to coat the ends with some impervious, moisture-resisting material. This is especially true in the case of small shaped blanks, where end checking is a serious defect. Black walnut gun stocks are always so coated (Fig. 17). A suitable coating must be impervious to moisture, must not melt off at the temperature used in the kiln, must adhere to the green wood, and must not be too brittle when dry. A good coating consists in a mixture of black baking japan and lamp black, to which a little linseed oil is added to prevent its chipping. Thin with turpentine for applying.

Another excellent coating consists of

Rosin (good quality)	100 parts by weight.
Lamp black	7 parts by weight.
Linseed oil	7 to 10 parts by weight.

The rosin should be melted at as low a temperature as possible, the oil then added, and the lamp black thoroughly stirred into the sticky liquid. On no account should the mixture be allowed to boil, since that will make it froth and the coating will be full of air bubbles and not impervious. Keep well stirred in a suitable kettle and dip the ends of the sticks at 220° to 240° Fahrenheit. The coating, when dry, should be perfectly smooth and shiny and an eighth to a quarter of an inch thick. Do not use paraffin for the dry kiln, as it melts at a very low temperature and the rosin mixture can not be successfully applied over paraffin. A trace of paraffin will cause the rosin mixture to melt at a very low temperature.

Another mixture which has been found to give excellent results is the following:

30 per cent. of 165° C. Pitch
70 per cent. of Rosin

Apply at temperature of 400° F.

May be brushed or dipped.

Fire Protection.—Modern moist air kilns are much safer from fire than dry air kilns. This is largely due to the reduction of the amount of oxygen present produced by the high percentage of moisture. To be convinced of this statement one needs only to carry a

lighted lantern into a moist kiln or to attempt to light a match. If this humidity is above 70 per cent. the lantern or a candle is likely to be extinguished and it will be exceedingly difficult to light a match. Where steam jets are available or water sprays are used the fire hazard is almost negligible. The condenser or spray-humidity regulated kiln is the safest kind and there is very little risk involved. In ventilated kilns particularly, where no attention is paid to humidity, the fire risk sometimes runs very high. Woodwork which has been subjected to the high temperatures usually prevailing in such kilns for a long time gradually becomes charred or partially distilled, and is very easily ignited. Spontaneous combustion is not uncommon under these conditions. In a bulletin on Lumber and Lumber Drying, issued by the National Fire Protection Association in 1914, it is stated that the common type of steam-heated dry room has an average fire life of but a little over five years. The use of the forced draught is said to be a most hazardous type and is apt to develop serious fires. Referring to the use of wooden timbers for track supports and wooden piles buried in the earth below the floor, the bulletin says: "A great many fires have occurred in kilns so built, the fire having been caused by the result of the gradual carbonization of the wood from the heat in the kiln. When it becomes charcoal the subsequent heat and moisture cause spontaneous ignition."

Again: "Lumber drying constitutes the principal hazard of woodworking factories. In furniture factories dry kilns are the source of 37 per cent. of all fires and in saw and planing mills 10 per cent. An average of all woodworkers gives 21 per cent. of all fires as originating in the dry kilns."

The causes of fires in dry kilns are given in the bulletin referred to—unknown, 56 per cent.; known, 44 per cent.—as follows:

	Per cent.
Steam pipes in contact with combustibles	30.3
Sparks entering kiln	28.8
Overheating	12.2
Oily material igniting	10.6
Fans or blowers	4.6
Defective flue from kiln	3.0
Miscellaneous	10.5
	100.0

Automatic sprinklers fed by adequate and independent water supply installed according to approved methods under direction of the inspection department of the National Fire Protection Association, having jurisdiction, are said to form the only thorough and reliable protection against fire. Edge stacked lumber is recommended as safer on account of the accessibility of the water from the sprinklers. The value of steam jets as a fire extinguishing agent in lumber kilns is considered as doubtful. Evidence, however, as to their actual efficacy is lacking. When a kiln can be tightly closed it is often possible to smother a fire without the use of any other means.

Construction and Costs of Dry Kilns and of Drying Lumber.—The efficiency of a dry kiln must be considered with respect to two considerations, namely, its (1) ability to accomplish the results desired and (2) the consumption of heat required in this accomplishment. The first may be termed its operative efficiency and the second its mechanical heat efficiency. There are cases when the first consideration alone will determine the choice of a dry kiln, as in the case of expensive woods or formed materials which must necessarily be dried and which is very difficult of accomplishment, or else where there is an excess of steam available which would be wasted otherwise. On the other hand, there are cases where the second item, the mechanical heat efficiency, alone controls the situation. The latter is the case principally with very cheap material which is easily dried and which is usually done wholly to save shipping weights. In this latter case the dry kiln may be looked upon simply as an apparatus for evaporating water in the quickest manner possible and with the least consumption of heat. Ordinarily, however, both factors come into consideration, and the problem of the selection of a dry kiln, other things, such as costs of construction, durability, operating expenses (other than heat consumption), rate of drying, adaptability to varying conditions, and fire risks, being equal, resolves itself into the question of the minimum heat consumption for the best results obtainable.

It is very evident, moreover, that a design of dry kiln which might give the highest heat efficiency for the best drying results for one set of conditions might prove the reverse for a different set of conditions. For example, a system which might prove most efficient for drying at a high temperature and high humidity might prove relatively inefficient where a low temperature and low humidity were required.

It is, therefore, by no means a simple problem to say what design of dry kiln will prove most efficient from the heat standpoint for any given set of conditions. Many experiments have been conducted by the Government in the development of the first requirement, namely, a kiln design which will accomplish the best results in drying, for any given problem, but little definite knowledge exists as to the most efficient kind from that standpoint for given requirements.

Previous Work.—So far as has been determined, there is nothing whatever in literature of a definite nature on this subject. Some data of a purely theoretical nature have been worked out by Hausband, "Drying in Air and Steam," and by the author in a Forest Service bulletin, "Theory of Drying and Its Application." Data are also available for most of the runs which have been made in the Forest Service Water Spray kiln at Madison, Wisconsin, as to the amount of heat consumed in the water, but only a few measure-

ments have been made of the total heat imparted to the kiln by the heating pipes and used up through radiation, leakages, and evaporation. (The heat of evaporation is included in the spray water, or condensing water consumption.) Further experiments are being undertaken by the Government at Madison, Wisconsin, with the object of determining the heat consumption by various methods of drying, under similar conditions.

The reason there is so little knowledge available on the heat consumption in commercial kilns is doubtless due to the loose manner in which they are usually operated and also to the fact that as a rule the steam consumption is of no consequence, low-pressure exhaust steam from the engine frequently being used to supply the kilns which would otherwise be wasted, or where high-pressure steam is used, there has been an unlimited supply of fuel in wood trimmings and sawdust.

Where the exhaust steam from the engine or a pump is turned into the heating pipes of the dry kiln, an immense saving of heat is secured thereby. The steam engine fails to utilize the larger portion of the heat contained in steam, namely the *latent* heat. It uses only the heat of expansion of the steam, and the steam leaves the engine still in the form of vapor. Where this is used for heating, however, there becomes available at once approximately 1000 British

thermal units of heat per pound of steam, due to its condensation, and the heating fluid is discharged from the system through the steam trap or exhaust pump, no longer as vapor, but in the form of water. Thus the same amount of steam may be made to do double duty, yielding its energy of expansion in operating the engine and its latent heat in heating the kiln. The water coming from the kiln will still be hot, at the boiling temperature, and may be used for the feed water for the furnace. It may even be desirable to carry a considerable back pressure on the engine of seven to twelve pounds in order to secure sufficiently high temperature in the heating pipes in the kiln. For high temperature drying it is generally necessary to use high-pressure steam in order to produce a reasonable amount of radiation, as otherwise an excessive amount of heating surface would be necessary.

It is not necessarily the cheapest kiln which is the best investment, or the most economical in the long run. The choice of the building material and of the kind of construction will depend largely upon the permanency of the operation. If the kiln is for a temporary undertaking, such as for a temporary mill working on a limited supply of lumber, a cheap wooden structure would probably be the most economical, since wood construction is the best insulator, and if the kiln simply lasts out the allotted time, that is all that is

necessary. In such a situation there would probably be no sales value to the plant after the operation is completed, even if built of permanent material. A cheap wooden structure can be built to last from four to six years. Well-built wooden kilns may last twenty or thirty years if properly taken care of and repaired, but they are always a fire hazard.

When a kiln is built in connection with a permanent operation, as at a wood-working factory, it is desirable to build of permanent masonry construction. The following materials are in use for dry kilns: Wood, studding sheathed on both sides; wood, solid crib construction, made of two-inch plank laid one on top of the other, thus making a wall of solid wood six or eight inches thick; wood, studding, sheathed inside and with metal lath and plaster outside; brick, solid, or with air space; concrete, solid; hollow concrete block; hollow tile; sheet iron, two plates filled between with mineral wool.

From the heat economy standpoint the insulation of the kiln is of great importance. Experiment has shown that the loss of heat through radiation from the roof, walls, and floor, and through leakages may, in cold weather, exceed the amount necessary to evaporate the moisture from the lumber. Ordinarily, however, the latent heat of the moisture evaporated from the lumber and the heat in the spent air as it leaves the

pile is more than sufficient to supply these losses. This is largely owing to the reason that the heat made latent through the evaporation of the moisture from the wood is available for helping heat the kiln walls, the evaporated water acting merely as a carrier or agent for carrying the heat from the steam pipes to the kiln surfaces or to the condensers. If the kiln is properly arranged the ceiling and side walls act as condensers, and the greater the radiation from the walls the less the required capacity of the condensing pipes or spray water.

There is a great difference in different materials and kinds of construction in their resistance to heat transmission. Solid dry wood is one of the very best insulators, and standard wall construction consisting of studding, double sheathing and plaster is also excellent. Of fireproof materials, solid stone and sand concrete is the poorest insulator and standard hollow hard burned tile is the best. Brick with air space is intermediate. Stone is from 50 to 100 per cent. more conductive than brick.

A great deal depends upon the weather. In northern climates in wet, windy weather, or during very low temperatures and high winds, the heat losses are enormous. In mild freezing, windy weather a small brick kiln with hollow wall and concrete roof sixteen feet high, eight feet wide, and eighteen feet long, heated to

160° to 180° F. inside, with high circulation, required 2500 pounds of steam per day, or an equivalent of three boiler horsepower when empty, merely to supply radiation and leakages. Where there are a number of kilns built together with common walls, the loss will be much less than with a single kiln.

In a brick kiln fifteen and a half feet wide, thirteen feet above the pipes, and eighteen feet long, with an outside temperature of 70° and inside 114° and saturated air, it required fifty-one pounds of steam per hour to supply radiation and leakages. In another test at 132° and 96 per cent. humidity it required 46.8 pounds per hour.

In a commercial kiln 107 feet long, holding twelve cars and 53,282 feet of inch oak, time of drying 21 days and 14 hours = 518 hours, the total steam consumed was 127,600 pounds = 246.3 pounds per hour. The approximate amount of water evaporated was 41,093 pounds; average temperature 158° F. Approximately 3.08 pounds of steam were used for each pound of water evaporated. This was a condensing kiln, but the material of which it was constructed and other data are lacking.

Besides the heat loss there is another very important factor in the material of which the kiln is built and that is its absorptive capacity. It is very difficult to hold a high humidity in a kiln with absorption walls.

The moisture passes into the walls from the air very rapidly, transfuses through them, and is evaporated from the outer surface. This also adds considerably to the heat loss, as the evaporation of a moist wall is a powerful cooling factor. For this reason it is always desirable to thoroughly coat the inside of a dry kiln with a waterproof paint. High melting asphaltum varnish or black baking japan is suitable for this purpose. Cement or concrete is the most absorbent of the building materials and unless thoroughly coated with moisture-resistant paint, or composed of a damp-proof mixture, it is unsuitable for a moist air kiln. A cement or a sand floor is also highly absorbent, and a kiln built on sand, without flooring, will lose its humidity very rapidly and is also harder to heat than one with an impervious bottom.

The table on page 96, averaged from a number of reliable data, gives the heat conductivity of various kinds of walls, in British thermal units per square foot of surface per hour per degree difference in temperature.

Figures given by different authors vary so greatly that no great reliance can be placed upon any one figure. Glass conducts from ten to fifteen times as much heat as dry wood, and sheet iron radiates about 10 per cent. more than glass.

In regard to cost of construction, this will vary,

	Solid brick	Slag or cinder concrete	Solid concrete (stone and cement)	Concrete with air space	For stone use
Wall 8 inches thick	0.43	.29	0.89	.54	1.5 to 2 times values given for brick
Wall 12 inches thick	0.31	——	0.77	.50	
Wall 16 inches thick	0.26	——	0.67	.46	
Wall 20 inches thick	0.23	——	0.59	.42	
Wall 24 inches thick	0.20	——	0.54	.39	
Stud partition, lath and plaster two sides	0.34				
Walls of average wooden house	0.30 (.25 to .44)				
Wooden door 1 inch thick	0.41				
Window glass, single	1.1				
Window glass, double	.59				
Concrete floor on brick arch	0.2				
Wooden beams planked over as floor	0.08 to 0.17				
Single ¾-inch wooden floor, no plaster beneath	0.45				
Single ¾-inch wooden floor, with plaster beneath	0.26				

of course, with local conditions, such as cost of labor and materials. The kind of kiln will also make some difference.

In general the kiln may be divided into the following items: Building proper, foundation, walls, roof; heating apparatus; doors, rails, trucks, etc. About half the total cost of a brick building may be allowed for the apparatus and accessories.

A recent estimate (December, 1916) on a plain kiln room 100 feet long, twelve feet high, and twenty feet wide, with back wall but with front open, is given on the following page:

Foundation, concrete and excavation	$250
Walls:	
Wood studding sheathed inside 1″ matched hemlock, outside 1″ hemlock covered with one thickness building paper and hemlock shiplap	595
12″ hollow tile	700
12″ concrete block	924
12″ brick with air space	1000
Roofs:	
Frame construction	280
Concrete beam and tile	900
Reinforced concrete slab	1000
Steel frame and book tile	800
Waterproofing Roof:	
Four-ply composition of tar and gravel	80

The foundation and waterproofing would be the same in any case.

For all wooden construction the cost of the building would be	$1205
For hollow tile and tile roof	1930
For concrete blocks and concrete slab roof	2254
For brick and cement slab	2330
For heating pipes and apparatus allow	1200

Then the total costs are as follows:

All wood	$2405
Hollow tile	3130
Concrete block	3454
Brick	3530

Other sizes would be in proportion; where several are built in a bank there would be the saving of the adjacent walls.

The following is the actual cost of certain kilns in 1910. There were two adjacent kilns having one common wall 150 feet long, sixteen feet high, eighteen feet wide, built of eight-inch hollow tile walls, cement foun-

dation, hollow tile roof with reinforced concrete girders covered with three-inch cinder cement slab overlaid with four-ply roofing:

Building	$4900
Trucks, piping, and apparatus	2918
Two doors	100
	$7918

It is estimated that in 1913 this would have cost $9900, and at the present time considerably more.

Cost of Operation.—The consumption of steam in well-insulated kilns in operation below 160° F. may be roughly taken as three to three and one-half times the amount of water evaporated from one-inch green lumber. For thicker sizes a greater proportion is required, and where the drying is carried much beyond the 6 per cent. of the dry weight, it may be greater than this; where very high temperatures or superheated steam is used it may run up to as high as four or five times the water evaporated.

As there is frequently an excess of steam available or the exhaust from the engine is used for heating the kilns, the cost of the steam is frequently not included in estimates of drying. Repairs, deterioration, interest on investment, insurance, should, however, be included. In some estimates a portion of the overhead ("administrative") charges of the business is included in the cost of kiln drying. The cost of labor

in piling and handling the lumber through the kiln must, of course, always be included. From this it will be seen that the actual cost of kiln drying the lumber is rather an elastic item, and can hardly be given in general terms. Estimates for drying hardwoods vary from 50 cents to $7.50 per M. A firm has been drying lumber for the trade at the following rates: Poplar $2.50, oak $3.25, for inch lumber, adding 25 per cent. for each additional quarter inch in thickness. Evidently this could be done at a profit or the concern would not have done it for the trade. No guarantee of any kind, however, was given, and considerable checking frequently occurred. Where a manufacturer does his own drying in connection with a saw mill or a woodworking plant, a reasonable expense for kiln drying one-inch hardwoods would be between $1 and $1.50 per M. An estimate given by a dry kiln manufacturer for condensing kilns is $1.04 per M in 1914.

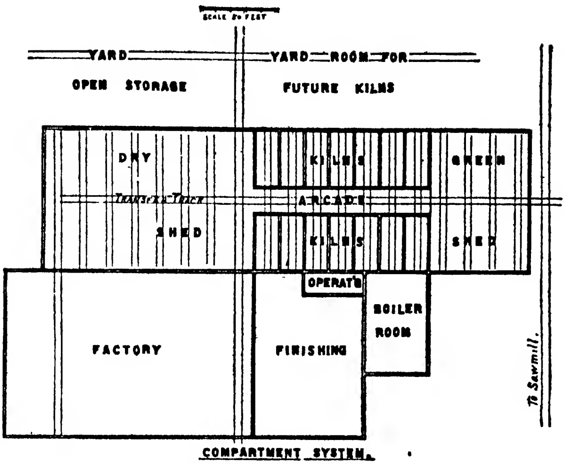
In regard to the costs of handling lumber in the kiln over against piling in the yard, this would ordinarily mean piling and unpiling once. With suitable arrangements there would be no additional piling necessary; that is, where the plant is so arranged that the lumber is loaded upon the kiln truck directly from the chains of the mill and again unloaded from the kiln truck, which may have been kept several days in the dry shed, directly into the railroad car. Where

the lumber is first piled out in the yard and then loaded into the kiln, and again piled in the dry shed, where it remains until called for, the cost of the loading and unloading must be included in the expense of the kiln drying as against air drying. This will ordinarily cost from 50 to 70 cents per M. The cost of air drying, not including depreciation, taxes, or insurance, nor interest on investment, but covering sorting and grading at the mill, handling and loading on the cars for shipment in a large oak and gum manufactory in the South, is $1.49 per M.

Two men can load or unload and sort 20,000 to 25,000 feet of one-inch lumber per day. With machine stackers two men with two machines can stack 80,000 to 120,000 feet per day.

General Layout of the Plant.—The arrangement of the kilns with respect to the saw mill, power house, factory, and yard mill, of course, varies with local requirements. It can usually be arranged with a little thought so as to give a minimum in handling of the lumber. The kiln should be near the boiler or engine room; there should be provision made for reasonable expansion without altering the convenience of the system of handling. There should be ample dry storage room and it will be found convenient to have a green loading room under cover as well as an open storage to take care of fluctuations in the operating

Fig. 18.



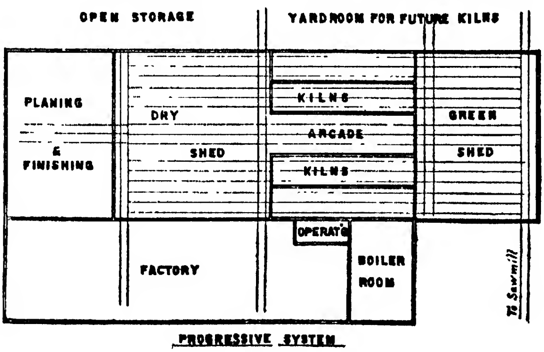


Fig. 19.

Fig. 18.—General layout of plant with progressive kilns.
Fig. 19.—General layout of plant with compartment kilns.

capacities. The accompanying diagrams are suggestive of a convenient layout of a plant designed to dry 12,000 board feet per day, assuming fourteen days as the length of time necessary to hold in the kilns. Figure 18 represents a battery of four progressive kilns each eighteen feet wide, ninety-two feet long, holding fourteen trucks, with 3000 board feet to each. These are ventilated end draught kilns, with lumber cross piled, flat. Figure 19 represents a battery of fourteen compartment kilns, fifteen feet wide, thirty-four feet deep, each holding two trucks of 6000 feet each, end piled slant piling spray or condenser kilns. The advantages of the compartment kilns are: (1) Less handling of the lumber, the trucks remaining stationary for fourteen days, whereas in the progressive kilns *all* of the trucks have to be moved *every* day. (2) Much better control of the temperature and moisture conditions. (3) Accessibility of each *entire* kiln every fourteen days. (4) Various kinds and thicknesses of material may be dried at the same time, each in a different compartment. For wooden kilns, insurance requirements may necessitate a different arrangement, with separation of the kilns from the rest of the plant.

CHAPTER IV

How Wood Dries; Shrinkage, Warping, Casehardening

Green wood contains water in two forms, namel as *free water;* that is, as small particles of liquid wat occupying the capillary spaces in the wood, as t lumina of the fibers and the vessels; and as *hygroscop moisture* intimately absorbed by the substance of t cell walls. The hygroscopic moisture appears to molecularly distributed between the particles or minu lamina of which wood substance is built up, in t same manner as it enters into colloidal substance It can be extracted from the substance without chan ing its chemical properties, but the substance begi to shrink with the slightest loss of this moisture. Mor over, it requires an additional amount of heat[1] th that necessary to evaporate free water in order extract this moisture from the wood substance. other words, the wood substance has an affinity f moisture and is capable of condensing a certain amou from the vapor in the air. In fact, there is a defini relation between the relative humidity of the air a the amount of moisture which the wood will retain.

[1] 33.7 B.t.u. per pound of dry wood or about 135 B.t.u. per pound water extracted, according to figures obtained by Frederick Dunlap.

The relationship between the relative humidity and the percentage of moisture retained is given for cotton (pure cellulose) and for several species of wood at 212° F. by H. E. McKenzie in Figure 20.

TABLE VI.—THE FIBER SATURATION POINT FOR SEVERAL WOODS AS DETERMINED BY COMPRESSION TESTS ON SMALL SPECIMENS.

Species	Condition	No. of tests	Average specific gravity kiln dry	Average moisture per cent. at fiber saturation point
Longleaf pine	Green	40	.62	25
Red spruce	Green	40	.38	31
Chestnut	Green	40	.48	25
Lobolly pine heart	Green	24	.59	23
Lobolly pine heart	Air dry	80	.67	24
Loblolly pine sap	Green	72	.47	24
Loblolly pine sap	Air dry	80	.55	26
Norway pine heart	Green	121	.42	30
Norway pine sap	Green	88	.44	28
Tamarack	Green	121	.54	30
Western hemlock	Green	144	.54	29
Red fir	Green	65	.58	23
White ash	Green	49	.79	20
Red gum	Air dry	45	.52	25
Red spruce	Air dry	120	.45	30 to 32
	Super-heated	120	.44	24 to 25
Tamarack	Air dry	120	.60	30 to 32
	Super-heated	80	.61	24 to 25
Chestnut	Air dry	120	.48	26 to 27
	Super-heated	120	.46	22 to 24

Other phenomena take place when the hygroscopic moisture is extracted: The strength begins to increase, so that perfectly dry wood may become four times as strong as it was when green. The wood substance of most species has a limit in the amount of hygroscopic moisture which it can contain. This limit is called

the *"Fiber Saturation Point."* It varies from 20 to 30 per cent. of the dry weight of the wood. See Table VI. In rare cases it appears to be as high as 90 per cent., since shrinkage begins at this point, for example,

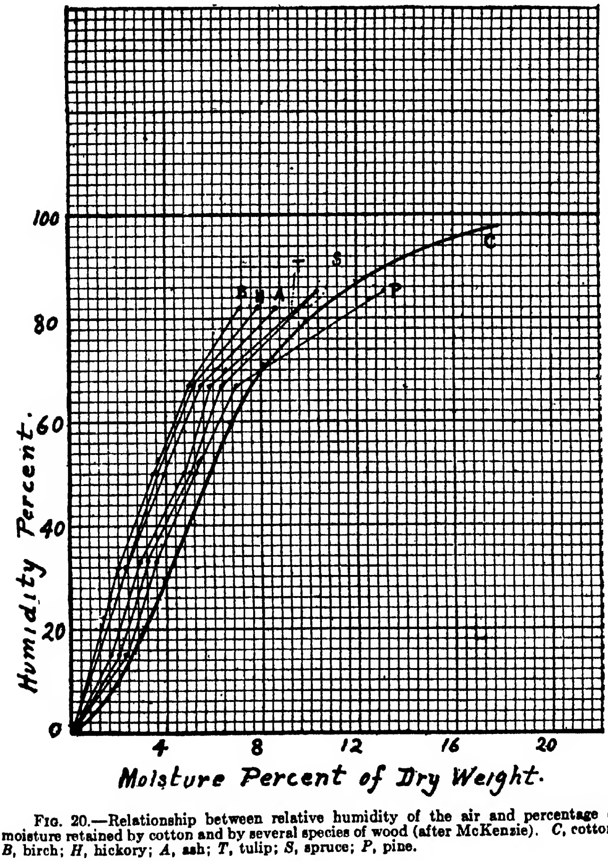


FIG. 20.—Relationship between relative humidity of the air and percentage of moisture retained by cotton and by several species of wood (after McKenzie). *C*, cotton; *B*, birch; *H*, hickory; *A*, ash; *T*, tulip; *S*, spruce; *P*, pine.

in *Eucalyptus globulus* and a few other eucalypts, and it is abnormally high also in some of the southern swamp oaks.

In the living tree the amount of moisture in the wood may range from 250 per cent. of its dry weight to about 30 per cent. The heartwood of conifers is usually near to its fiber saturation point, containing about 30 per cent. of moisture, but the sapwood, which contains much free water, often has from 100 to 150 per cent. In the hardwoods sometimes both heart and sapwood contain 60 to over 200 per cent. moisture, but frequently the sapwood contains more free water than the heartwood. No wood in a healthy condition in the living tree is drier than its fiber saturation point. Dry wood is, therefore, from the physiological standpoint, in an abnormal condition, it has never been dry before since its creation from the cambium cells of the tree.

Season of Felling and Moisture.—There is a widespread opinion that wood in the summer time contains more water than in the winter. This is not the case; in fact, during the period of most active growth in the spring the tree sometimes contains *less* water than it contained during winter.[2] It is true that the "trans-

[2] Investigation by Hartig in Die Technichen Eigenschaften des Holzes by H. Nordlinger, 1860. Also see investigation by Gabriel Janka on "Einwirkung von Süss- und Salwässern auf die Gewerblichen Eigenshaften der Hauptholzarten" in Mittheilungen aus dem Forstlichen Verschuchswesen Osterreichs, Folge xxxiii heft.

piration current," or the "sap" is moving much more rapidly at the time of active growth. The expressions that the "sap is up" in spring and that it reposes "in the roots" in winter are incorrect. Marked chemical changes take place in the sap of the tree between summer and winter, but the total amount of water in the wood does not change greatly with the season. In the winter the food is stored in the sapwood as insoluble starch and gums, and in the spring these are reduced again to sugars, which are soluble and are carried through the living tissues. This is one reason why sugar is so plentiful in maples at certain seasons of the year. Great changes in internal pressures occur within the tree, especially in the early spring when the sap is flowing. Actual pressures have been measured in maple trees from a partial vacuum of five pounds below atmospheric to twenty-five pounds gauge above. In one case this extreme variation in pressure of thirty pounds per square inch occurred between early morning and noon of the same day. This change in pressure is what causes the flow and it is partly due to changes in temperature.[3]

Probably what changes in moisture do occur are confined to the sapwood only. There is considerable

[3] Bulletin No. 105, Vermont Agricultural Experiment Station Burlington, 1904, "The Maple Sap Flow," from researches by C. H Jones, A. W. Edson, and W. J. Morse.

difference of opinion as to relative merits of cutting timber at different times of year. Probably the most common opinion is that winter cutting is the best "because the sap is down." Some long experienced and observing lumbermen, however, state that the summer felled timber is the best.

So far as the amount of water present in the heartwood is concerned there is in reality no difference. There is this to be noted, however, when a tree is felled which is in full leaf and allowed to remain until the leaves shrivel up, practically all of the free water is drawn off from the sapwood by the rapid transpiration of the leaves. Thus the outer layer of the logs will dry very quickly and danger from stain or rot is greatly reduced or eliminated. The heartwood is not affected by this treatment. The same thing is accomplished by girdling the standing trees, cutting clear through the sapwood. This is a common practice in the teak forests of British India, where the trees are girdled one or two years before they are felled.

On the other hand, if the tree is immediately sawed up into logs, the sapwood contains much soluble foods which render the logs very susceptible to fungous attack, causing stain and rot, during the summer. In this case, winter felling is, no doubt, preferable, as the logs have a chance to season slightly during cold weather, so that when the warm weather favorable to

fungous growth arrives the surfaces of the logs will have dried down below the danger point.

The butt portions of trees which grow in damp ground frequently contain much more free water than the tops of the trees or than trees growing on drier ground. These butt portions are usually full of shakes and may contain 100 to 200 per cent. moisture, whereas the tops contain only 30 per cent. Such trees frequently have swelled butts. This is particularly true of western red cedar, western larch, tupelo, cypress, sugar pine, white elm, redwood, hemlock, etc.

Soaking in Water.—Another current belief is that long-time soaking causes wood to dry much quicker and renders it less subject to warping and "working." Wood which has been buried in swamps is eagerly sought after. While there is no direct evidence that soaked wood seasons any more rapidly than green wood, it seems very probable that long leaching for years may reduce the tendency to check and to warp. The tannins, resins, gums, and albuminous materials undergo a gradual change under water, and much of the deposited materials is gradually leached out. The internal stresses also gradually disappear. The appearance of driftwood, particularly of logs which have long been under water, strengthens the theory. The wood appears to become more porous, due to the leaching out of these substances, but it must require a very

long time, many years for whole logs, to accomplish these results.[4] That is why it is difficult to find any exact comparative data. Boiling in water or soaking in hot water accomplishes a somewhat similar result in a much shorter time. In Japan it is a common practice to soak wood for two to five years, before using, in large municipal tanks, in a mixture of six parts sea water and one part fresh water. The sticks are turned and cleaned occasionally. Just how much this treatment is responsible for the world-wide reputation of Japanese wooden articles is uncertain.

How Wood Dries.—In order to get an understanding of the phenomena which take place as wood dries, let us consider a piece of green lumber containing 75 per cent. of water, 25 per cent. being hygroscopic and 50 per cent. free water, and follow the process as nearly as we can, step by step. The evaporation must take place from the surface and the water in the interior must pass from cell to cell until it reaches the surface. In order that there shall be any movement of the water within the stick there must be a gradient of moisture condition or a difference of temperature between any two portions. Therefore, the surface must be drier than the inside. Just how the moisture passes through the wood is not known. It may all pass through the cell walls as hygroscopic moisture,

[4] See reference to Janka's researches, footnote, page 106.

or the free water may pass through the pits in the walls by capillarity, as it passes off from the surface. What probably happens is this: the free water evaporates first from the surface and if the rate of evaporation is greater than the rate at which the internal free water can pass to the surface, the hygroscopic moisture also begins to evaporate from the surface, which then begins to shrink and surface check. In this condition the columns of free water become interrupted, and a retardation of the transfusion of free water from the inside takes place. This is one phase of "casehardening." On the other hand, if the surface evaporation is not too rapid, a continuous flow of the free water from the center to the surface takes place, until all of the free water has passed off. It is evident that the hygroscopic moisture must pass outward only through the substance of the cell walls themselves, and not as the free water through the capillary spaces. Evidently this would be a much slower process, which supposition is borne out by the drying curves, which all drop off in rate quite suddenly near the fiber saturation point. (See Curves, Fig. 31.) The transfusion endwise of the grain is very much greater, probably ten or twenty times as rapid as it is across the grain, as is evidenced by the end checking of lumber, and it is more rapid radially than it is in the direction of the circumference or tangentially. This is why quarter-

sawed or edge grain lumber dries more slowly than slash-sawed or flat grain. But end drying can not be ordinarily counted upon for removal of the moisture from lumber and it must nearly all pass out in a direction across the grain. This process of transfusion is very slow, so that it requires from three months to several years for one inch thick lumber to dry in the air. I have found that moisture passes from the warmer towards the colder portion of a block of wood. If it be heated on one side and cooled on the other, the water will be driven from the heated side to the cold surface. If a hot piece of wood containing some moisture be placed upon a cold piece of iron, the moisture will be very quickly condensed upon the cold metal surface. This is a very useful quick test to determine whether a piece of wood from the kiln is dry. A freshly-sawed end-grain surface should be used for this test. The cause of this phenomenon is not certain, but a possible explanation is the following: Consider a series of cells joined side to side in a row and heat applied at one end and cold at the other. The moisture is vaporized from the hot side of the first cell and the cavity within is saturated with the vapor. The opposite surface being slightly cooler, condensation must take place thereon. The condensed moisture then soaks through the common wall and is re-evaporated in the next cavity and again condensed on the further

wall. This is repeated clear through the series of cells until finally the moisture is condensed on the cold metal surface or is evaporated in the cold air. If a piece of wood containing free water be steamed under slight pressure until it becomes heated through to the center and then taken out from the steam and placed in a cooler atmosphere, the moisture is driven from the interior towards the surface so long as there is a difference in temperature between the inside and the surface. This effect is highly beneficial, but can not well be repeated, after the block has once cooled down, since the second heating tends to drive the moisture back again towards the center.

A disk three inches thick, cut across a freshly felled basswood tree, was split in two parts through the center. One part was steamed twenty minutes at twenty pounds gauge; then both halves were stood on edge on a table in a warm, dry room. The disk contained 97 per cent. moisture when cut. In eight days the unsteamed piece had dried to an average of 19 per cent. moisture and was full of numerous fine checks or crackles on both surfaces, large enough to insert the point of a lead pencil. Marks on the surface made with cobalt chloride had turned blue, indicating that the surface was dry, the inside being still quite moist. The steamed piece dried a little slower than the unsteamed, but developed no crackles other than two very fine checks, even after

complete drying. Moreover, cobalt chloride marks on the surface remained pink long after those on the other piece had turned blue, indicating a moist condition of the surface even when the entire block had dried to considerably less than the fiber saturation point. Finally the crackles on the first piece closed up again, showing that the interior was drying and beginning to shrink. This experiment shows plainly the effect of the internal heat in driving the moisture towards the cooler portions. Hence the desirability of having the lumber heated clear through before drying begins.

A study of the microscopic structure of wood shows why the drying takes place so much more rapidly endwise than across the grain.

Casehardening.—As a green piece of wood dries, shrinkage as a rule[5] does not begin until the fiber saturation point has been reached. If the conditions of drying are such that the evaporation from the surface exceeds the rate at which the water in the center transfuses outwardly, the free water on the surface will all disappear before the inner water can take its place. The water films or columns thus become broken with air in between, so that the remaining water has

[5] In some woods, notably western red cedar, a collapsion of the cell cavities begins to take place as soon as drying begins, which causes the stick to appear to shrink at once. This is not true shrinkage, however, as it is a totally different phenomenon. Eucalyptus, "blue gum," appears to begin to shrink at 80 to 90 per cent. moisture, due to a form of collapse.

to pass out gradually by seepage along the cell walls and further transfusion of the free water from the inside is thus retarded. This is the first stage of case-hardening.

As drying then progresses beyond the fiber saturation point, the outer shell tends to shrink, but is prevented from doing so by the wet interior. Strong tension stress is therefore set up in the outer surface with compression in the inner portion. This condition

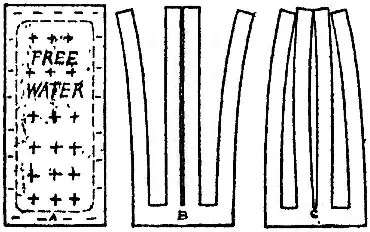


FIG. 21.—First stages in casehardening. The figures represent a disk cut across the timber perpendicular to the grain.
(A) Surface dried below the fiber saturation point and in a state of tension. Interior containing free water and in compression. Tension stress indicated by minus sign (−); compression by plus sign (+).
(B) If disk A be immediately sawed by five slits, as shown, it will at once spring into this shape.
(C) If B be now dried in an oven or warm room, the tongues will finally bend into this shape and remain so permanently.

is shown by Fig. 21-A, which represents a disk sawed across a plank of wood at this stage.

If this disk be immediately slotted, as shown at Fig. 21-B, by running five parallel saw cuts nearly through, and breaking away two of the tongues thus formed, the outer prongs will at once bend outwardly as shown in the figure. This indicates temporary case-hardening, due primarily to a dry surface and wet

interior. If this disk be then placed in a dry room where it will dry out, it will finally assume the form shown at Figure 21-C.

Wood is a plastic substance when hot and moist. When dry it becomes very much harder, stiffer and stronger than when wet. Consequently, when a stick of wood is bent while hot and wet, and then dried in this position, it will rigidly retain the form into which it was clamped when drying. This well-known principle, made use of in wood bending, also applies in the case of casehardening. The outer shell, which dries first below its fiber saturation point and thus tends to shrink, is prevented from so doing by the wet interior. As it continues to dry it hardens in this expanded condition. (See Fig. 21-A.) The interior now continues to dry very slowly, and tends to shrink, but is in turn prevented from doing so by the hardened outer shell which has "set" in its expanded condition. The result is that the stresses within the block are now reversed, the outer shell being in compression and the inner portion in tension, as shown in Figure 22-A (compare with Fig. 21-A). If the tensile strength of the wood across the grain is sufficient to withstand these stresses, the wood will dry in this condition containing permanent internal stresses, but if it is weak it will yield to the tension stresses and split open as shown in Figure 22-B, usually along the medullary

rays. This is the explanation of honeycombing or "hollow horning."

A peculiar physical property which accentuates this result of permanent casehardening is the fact that *the slower wood dries, the greater is the shrinkage.* Consequently, not only does the stress result from the expanded set condition of the outer shell, but also from

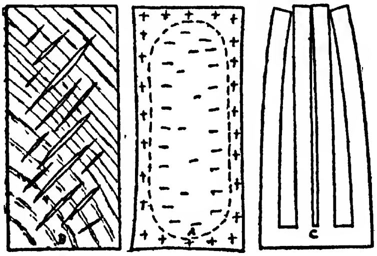


FIG. 22.—Final stage in casehardening and honeycombing. This is the condition of permanent casehardening

(A) Permanent internal stresses remaining after the wood has completely dried. Tension stress indicated by minus sign (–) and compression by plus sign (+). Compare with Figure 21 A and note that the stresses here are completely reversed.

(B) Honeycombing resulting from the stresses shown in A; the strength of the wood across the grain was insufficient to resist the internal tensile stresses and the fibers have separated along the medullary rays.

(C) If disk A be sawed by fine slits, as shown, it will immediately assume this form and bind on the saw.

the fact that the interior tends to shrink more than the shell, due to slower rate of drying.

The phenomenon of collapse [6] also probably enters into this honeycombing in certain species, such as western red cedars, causing excessive shrinkage of the interior portion.

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[6] See article by the writer, "Problems in Kiln Drying Lumber," in the *Lumber World Review* for September 25, 1915.

Proof of Stresses in Casehardened Wood.—To prove that the stresses exist permanently, as explained in the casehardened wood, it is only necessary to take a disk A, Figure 22, and slot it, as described before. The prongs will at once turn inward, as shown in Figure 22-C, frequently with such force that it is difficult to remove the piece from the saw. This disk will

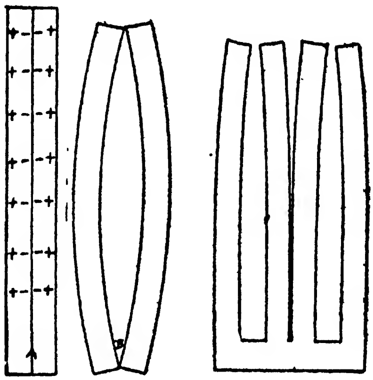

FIG. 23.—End view of a casehardened board—(A) Internal stresses; minus sign (−) is tension and plus sign (+) is compression.
(B) Form which the board will assume after resawing.
(C) Test for internal moisture—note the bending outward of the center tongues upon exposure to dry air. They will ultimately turn inward as in Figure 22 C.

remain definitely in this condition so long as it is kept dry.

If the plank was not thoroughly dry when the disk was sawed, as shown in C, these prongs will close up still further as the disk dries. Compare this figure with B in Figure 21, when the stresses were temporarily of the opposite kind.

From this explanation it is perfectly plain why a casehardened board will cup when resawed, as in Figure 23. For the same reason, when articles are manufactured from casehardened wood, they are very apt to warp and give trouble. The two inner tongues of the slotted disk give an excellent indication of whether the interior of the wood is dry. If the interior is not dry, the tongues will show little or no tendency to bend on the saw, but after remaining in a dry room for a short time they will begin to bend outwardly as shown in Figure 23-C.

They will finally, however, bend inwardly as shown in Figure 21-C, as the disk dries out. If they remain parallel in a dry room it indicates that the wood was thoroughly dry (that is, corresponding to the room condition) when the disk was cut. The explanation of the behavior of these tongues as described above is significant.

In Chapter VI I have stated that drying should take place uniformly from the opposite faces and that if drying took place from one face only the board or stick would tend to cup—not with the first dried face as the concave surface, as might at first be supposed, but just the reverse. The surface which dried first will become the convex surface.

This phenomenon is exactly what takes place in the two parallel tongues of the pronged disk, and the

explanation is as follows: The outer surfaces, being exposed to the air, dry first below their fiber saturation point, and these surfaces dry in a stretched condition, being held by the resistance of the rest of the tongue to bending. That this is so is shown by the slight bending of the tongues outward (Fig. 23-C).

The dried surface hardens in this stretched condition. The rest of the tongue subsequently dries more

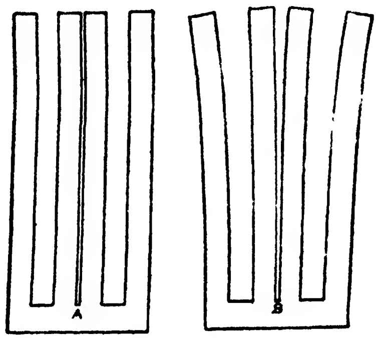

FIG. 24.—Test disks for removal of casehardening. In A the stresses have been entirely neutralized and casehardening eliminated. In B, the process has been carried too far and the condition has been reversed.

slowly and shrinks more than the outer surface; consequently the curvature ultimately becomes reversed and the tongues bend inwardly as shown in Figure 21-C. The rapidly dried surface of a board or stick (dried from the green condition) therefore tends to be convex and *not* concave.

This action is often of considerable consequence in the drying of wood, especially of material sawed into blanks for manufacture after drying.

Removal of Casehardening.—A clear understand-

ing of the nature of casehardening will, with a little thought, suggest a means by which it may be removed. In fact, it is not only possible, but entirely practicable, on a large scale, to eliminate casehardening, provided it has not gone to the extent of causing honeycombing. Very recently I discovered the method which I will now describe.

The only condition of permanently casehardened material which is of serious consequence is that it contains internal stresses. If these can be removed, the trouble will be overcome. With a knowledge of the distribution of these stresses it is evident that if we soften up the external shell containing the compressive stresses, so that it becomes plastic, the stresses will readjust or neutralize themselves and disappear. It has been pointed out that wood substance becomes plastic when hot and moist. Therefore, if the casehardened wood be placed in steam or in hot moist air for a while, sufficient time only to soften up the external shell, the result will be accomplished. The temperature necessary probably varies with the different species, as some become much more plastic than others at the same temperature.

The time of exposure necessary will vary with the degree of casehardening, but it is astonishing how quickly the result is obtained, usually in from ten minutes to half an hour in saturated air at 180° to 200° F. One great advantage of this treatment is that,

since the moisture need penetrate only the outer surface, it very quickly re-evaporates. Moreover, it can be done on any scale whatsoever.

Probably the simplest way is to place perforated steam pipes in the kiln or in a separate room into which the truck can be run, arranged in such a way as to produce a maximum circulation through the pile of lumber. High-pressure steam and plenty of it should be available.

For a couple of truck loads of lumber, each about $16 \times 8 \times 5$ feet in size, a one and one-half inch pipe with boiler pressure steam (eighty to a hundred pounds gauge) should be used, having in all about eighty one-eighth inch holes properly distributed, and this should be opened up full.

The temperature should be allowed to rise as rapidly as possible, and the steam turned off again after the proper time, which must be determined by experiment for a given kind of material and conditions. Drying conditions should then be re-established as soon as possible and the load left in the kiln for a day or two.

For two and one-half inch black walnut at about 5 to 6 per cent. moisture, I have found that steaming in this manner for half an hour, the temperature rising from about 130° to 180° during this time, gives satisfactory results. In from one to three days' time the absorbed moisture will have entirely evaporated and the material will be as dry as before steaming.

No fear need be had of injuring the finest woods by this treatment, and it is so simple that it is within the reach of everyone who has a dry kiln. There is no danger whatever of checking the wood, since the surface is already in compression, and all stresses are relieved thereby and not augmented.

If the process is carried too far a reversal of stresses may be produced. This can be readily determined by cutting the pronged disk. If stresses are reversed, the outer prongs will bend outwardly as shown in Figure 24-B. If exposure has been correct, the prongs should remain parallel as shown in Figure 24-A.

The test disks should not be cut until the moisture has re-evaporated.

Figure 8 shows the ultimate results of casehardening in three and one-quarter inch by three and one-quarter inch red and white oak wagon felloes, casehardened in the dry kiln, compared with similar ones properly kiln dried. On the left is shown the same result produced by air drying in the case of willow oak. In Figure 25 the effect of final steaming in removing and reversing the casehardening is clearly shown in maple and oak.

Warping.—As already explained, it is the internal stresses existing in the lumber which cause it to warp, twist, and cup. Casehardening is one basic cause of this.

Another cause of warping is the direction of the grain of the wood, coupled with the fact that the shrinkage is different in different directions. Curly grain is very apt to bring this about. An "interlocking" grain, that is, one where the fibers of the successive layers twist spirally around the trunk in alternate directions, is even more effective. This gives a very tough wood, but one which is very much inclined to warp, and it does not hold its shape well even after it has once been dried. This interlocking grain is very common in many hard tropical woods such as lignum vitæ, coca bola, and also in tupelo gum, and occasionally in red gum.

It often happens that the trunks of trees twist spirally. The elements of the wood then are all inclined to the axis in a spiral direction, irrespective of the fact that the annual rings may be uniform and concentric. A board or stick sawed from such a log may *appear* as straight-grained because the intersections of the annual rings with the plane surfaces will be straight lines, but the wood will always split diagonally and the defect is designated as "spiral grain." This condition is illustrated in Figure 26, which represents such a log. If a board be sawed as indicated by *M N O P*, it will intersect the annual rings in lines such as *W X Y Z* parallel to its edges, but the grain in reality will be slanting and the board will split in a plane such as *A B E F*. This defect is frequently a great surprise because its nature is not understood—why

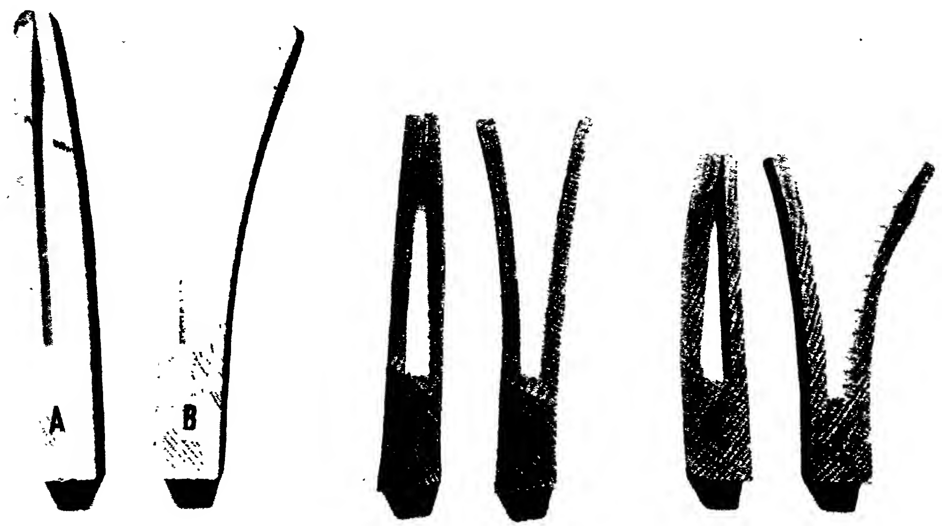

FIG. 25.—Reversal of Casehardening Shown by Disks. A, C, E, casehardened in kiln drying, B, D, F, from same boards after reversing the internal stresses.

an apparently straight-grained piece of wood such as birch or maple should split diagonally. A board sawed from such a log will evidently tend to warp in drying.

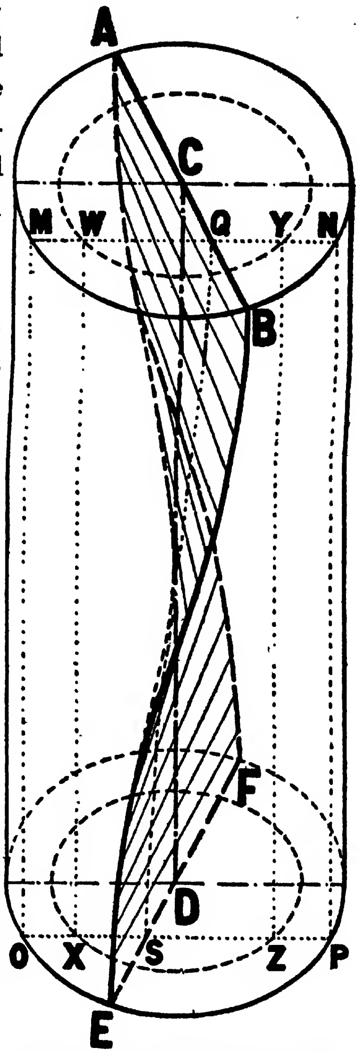

Fig. 26.—Diagram explanatory of spiral grain.

Shrinkage. — Unequal shrinkage lies at the root of all troubles with handling wood. The relative amounts which different species shrink in the three directions vary considerably, but in general it may be stated that wood shrinks tangentially twice as much as radially, and one hundred times as much as longitudinally. It is manifestly impossible, therefore, for a piece of wood to dry below its fiber saturation point with-

out producing internal strains. Were it not for its plasticity or colloidal nature, it would, therefore, always check in drying, but the wood is able to yield to these stresses and alter its shape accordingly. Imagine half a disk cut across a log forming a semicircle with the medullary rays arranged as in an open fan. Draw a straight line parallel to its diameter across the face of the disk. When this shrinks the radii will close together slightly, just as in closing the fan, and the straight line will curve outwardly from the center. This is just the way a board will tend to curve in drying, and squares, circles, or any other figures cut from the log will distort in drying in the same manner as though sketched upon the open fan and the fan then partly closed up. A quarter-sawed or radially-cut board, on the other hand, will remain flat, but will normally shrink more on the outer edges than at the center of the log. Figure 27 shows how the shrinkage affects the shape. One view is diagrammatic and the other is the actual shrinkage of a disk of oak cut across the log.

Not many data are available as to the longitudinal shrinkage of various species of wood, as ordinarily it is so slight that it may be neglected. For this reason, and on account of the very small thermal expansion, clock pendulums are frequently made of wood. Of our native species, redwood shrinks more longitudinally than the average, and mahogany is said to do the same.

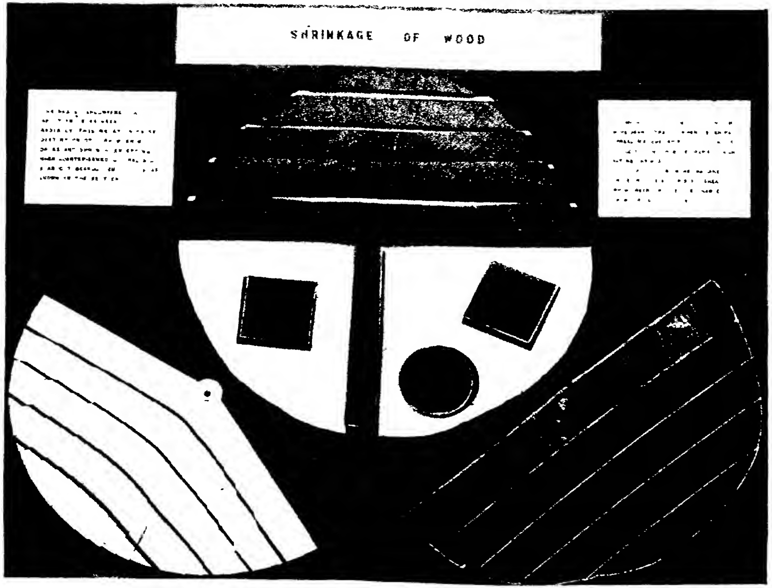

FIG 27.—How wood shrinks It closes up like a fan, viewed endwise of the log, and various shaped sections alter their forms accordingly

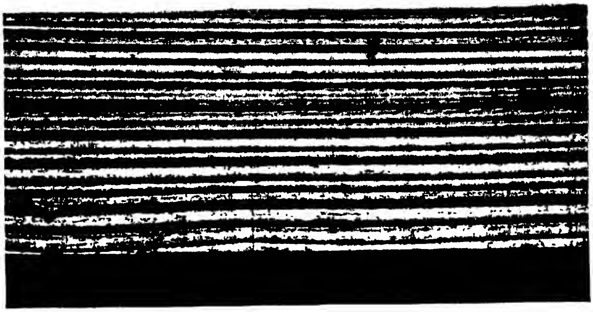

FIG. 28.—"Wash boarding" effect on a radially-sawed board of blue gum (*Eucalyptus globulus*)

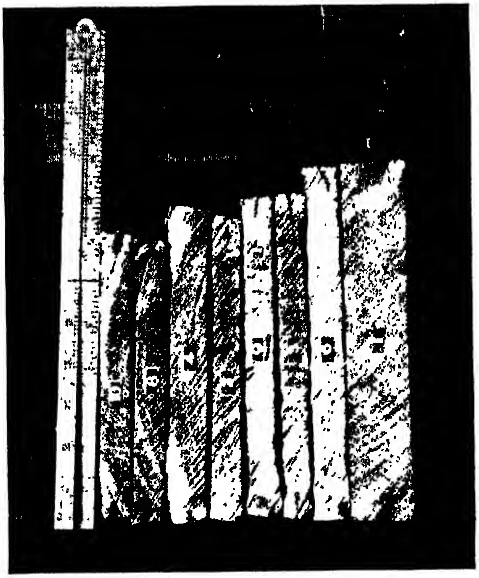

FIG. 29.—Remarkable shrinkage of California blue gum compared with redwood. All these boards were originally the same width. (The one on the right is redwood.)

The shrinkage of wood in drying varies almost exactly in an inverse ratio with its moisture per cent. Thus, if plotted on cross section paper with moisture per cent. as an abscissa and width as an ordinate, the diagram forms a straight line from the fiber saturation point to zero per cent. moisture.

The table (VII) on pages 129–131, which has been calculated from United States Forest Service tests,[7] gives the shrinkage from the green to the perfectly dry condition in the two directions across the grain and in volume, in per cent. of the green dimension. The volume was measured on two inch by two inch pieces, and the radial and tangential on pieces two inches wide and four inches long in the direction measured. The weights per thousand board feet of lumber, exactly one inch thick when green, are also given for the green, shipping dry (25 per cent. moisture), air dry (15 per cent.), and kiln dry (3 per cent.) conditions.

The pieces on which the shrinkage data were obtained were first air dried, and then placed in an oven heated to the boiling point until completely dry.

In general the relative amount of shrinkage between different species is somewhat proportional to density, the heavier woods shrinking the most, but there are some notable exceptions. Thus basswood, with a specific gravity of only 0.33, shrinks almost twice as much as black locust, with a specific gravity of 0.66.

[7] Circular 213, Forest Service, U. S. Department of Agriculture.

In a single piece of wood the reverse of this rule is often the case; in the case of blue gum (*Eucalyptus globulus*) the lighter wood of the concentric layers shrinks more than the dense heavy wood. Thus in drying it corrugates and a radially-cut board (quarter-sawed) greatly resembles a washboard (Fig. 28). This remarkable kind of wood shrinks more than any other known species, and the shrinkage is not only different in the three principal directions, but varies from layer to layer. Consequently, it is the most difficult kind of wood to dry, especially from trees less than fifty years old. Moreover, as already noted, the shrinkage begins at about 80 to 90 per cent. of moisture, instead of at 25 to 30 per cent., as in most species.

In some species, notably maple, oak, eucalyptus, and most of the conifers, the heartwood shrinks more than the sapwood, but in others, such as red gum, the reverse is the case. Where there is a difference in the amount of shrinkage between heartwood and sapwood, boards containing both are very apt to warp in drying. A quarter-sawed board, for this reason, will tend to bend sickle-shape. Thus radially-cut boards of red gum containing heartwood on one edge and sapwood on the other will bow outwardly in drying.

The amount of shrinkage in a piece of wood is not a constant factor, but it varies with the manner in which the wood dries. Thus, when dried slowly at high temperature and high humidity, wood shrinks much

TABLE VII.—SHRINKAGE FROM GREEN TO OVEN-DRY CONDITION

	Species	Botanical name	State	Specific gravity dry wood	Weight per M of kiln dry wood at 5 per cent. moisture 1 inch thick when green	Shrinkage per cent. of green from green to oven-dry			Green moisture per cent. of dry wood
						Volume	Radial	Tangential	
				*	Lbs.				
1	Ash, black	Fraxinus nigra	Mich.	.45	2460	15.2	5.0	7.8	91
2	Ash, white	Fraxinus americana	Ark.	.55	3000	12.6	4.3	6.4	38
3	Ash, white	Fraxinus americana	N. Y.	.58	3170	14.0	5.3	8.7	40
4	Aspen, large tooth	Populus grandidentata	Wis.	.35	1910	11.6	3.1	7.9	96
5	Basswood	Tilia americana	Penn.	.33	1800	16.5	6.8	9.9	99
6	Basswood	Tilia americana	Wis.	.32	1750	14.5	6.2	8.4	110
7	Beech	Fagus atropunicea	Ind.	.56	3060	16.5	4.6	10.5	61
8	Beech	Fagus atropunicea	Penn.	.53	2890	15.8	5.1	10.6	64
9	Birch, yellow	Betula lutea	Penn.	.55	3000	16.7	6.9	8.9	64
10	Birch, yellow	Betula lutea	Wis.	.55	3000	17.0	7.9	9.0	72
11	Buckeye	Æsculus octandra	Tenn.	.33	1800	12.0	3.5	7.8	141
12	Butternut	Juglans cinerea	Wis.	.35	1910	9.4	3.6	5.7	102
13	Butternut	Juglans cinerea	Tenn.	.36	1970	11.1	3.0	6.5	106
14	Cherry, black	Prunus serotina	Penn.	.47	2570	11.5	3.7	7.1	55
15	Chestnut	Castanea dentata	Tenn.	.39	2130	12.9	3.4	6.8	133
16	Cucumber	Magnolia acuminata	Tenn.	.44	2400	13.6	5.2	8.8	80
17	Elm, cork	Ulmus racemosa	Wis.	.57	3110	14.1	4.8	8.1	53
18	Elm, white	Ulmus americana	Penn.	.44	2400	14.4	4.2	9.5	92
20	Gum, black	Nyssa sylvatica	Tenn.	.46	2510	13.9	4.4	7.7	55
21	Gum, red	Liquidambar stryaciflua	Mo.	.43	2350	15.0	5.2	9.9	71
22	Hickory, shellbark	Hicoria lacinosa	Miss.	.60	3280	17.6	7.4	11.2	64
23	Hickory, shellbark	Hicoria lacinosa	Ohio	.67	3660	20.9	7.9	14.2	55
24	Hickory, mockernut	Hicoria alba	Miss.	.61	3330	16.5	6.9	10.4	64
25	Hickory, mockernut	Hicoria alba	Penn.	.66	3600	18.9	8.4	11.4	57

* Based on dimensions when green.

26	Hickory, pignut....	Hicoria glabra.........	Miss.	.63	3440	15.0	5.6	9.8	59
27	Hickory, pignut....	Hicoria glabra.........	Ohio	.67	3660	15.3	6.3	9.5	54
28	Hickory, shagbark..	Hicoria ovata.........	Miss.	.61	3330	16.0	6.5	10.2	65
29	Hickory, shagbark..	Hicoria ovata.........	Ohio	.65	3550	18.4	7.9	11.4	58
30	Hickory, shagbark..	Hicoria ovata..........	W. Va.	.65	3550	15.5	6.5	9.7	60
31	Holly.............	Ilex opaca.............	Tenn.	.50	2730	16.2	4.5	9.5	82
32	Locust, black......	Robinia pseudacacia....	Tenn.	.66	3600	9.8	4.4	6.9	40
33	Locust, honey.....	Gleditsia triacanthos....	Ind.	.60	3280	10.8	4.2	6.6	53
34	Maple, silver.......	Acer saccharinum......	Wis.	.44	2400	12.0	3.0	7.2	66
35	Maple, sugar.....	Acer saccharum....	Ind.	.54	2950	14.3	4.9	9.1	57
36	Maple, sugar......	Acer saccharum........	Penn.	.55	3000	14.7	4.8	9.2	67
38	Oak, bur...... . .	Quercus macrocarpa....	Wis.	.58	3170	12.7	4.4	8.8	70
39	Oak, red..........	Quercus rubra..........	Ark.	.57	3110	14.5	4.2	8.3	83
40	Oak, red.........	Quercus rubra..... . .	Ind.	.57	3110	13.1	3.7	8.3	80
42	Oak, red..........	Quercus rubra.........	Tenn.	.53	2900	15.3	3.7	8.3	85
43	Oak, swamp white..	Quercus platanoides...	Ind.	.64	3500	17.7	5.5	10.6	74
44	Oak, white........	Quercus alba...........	Ark.	.59	3220	15.8	6.2	8.3	58
45	Oak, white.......	Quercus alba..........	Ind.	.61	3330	14.3	4.9	9.0	62
46	Oak, white.......	Quercus alba....	La.	.60	3280	16.0	4.8	9.2	78
47	Oak, black........	Quercus velutina......	Ark.	.57	3110	14.2	4.5	9.7	77
49	Osage, orange.....	Toxylon pomiferum.....	Ind.	.76	4150	8.9	.	....	31
50	Sycamore.......	Platanus occidentalis....	Ind.	.45	2460	13.5	5.0	7.3	81
51	Sycamore.........	Platanus occidentalis ..	Tenn.	.46	2510	14.8	5.2	7.9	85
52	Tulip...........	Liriodendron tulipifera..	Tenn.	.37	2020	11.4	4.1	6.9	64
53	Tupelo....	Nyssa aquatica...	La.	.48	2620	12.4	4.4	7.9	121
54	Willow, black.. .	Salix nigra..........	Wis.	.33	1800	13.3	2.2	8.2	148
4a	Aspen	Populus tremuloides....	Wis.	.36	1970	11.1	3.3	6.9	107
10a	Birch, paper. .	Betula papyrifera .	Wis.	.47	2570	16.3	6.6	8.8	72
15a	Cottonwood, black.	Populus trichocarpa. .	Wash.	.32	1750	12.4	3.6	8.6	132
15c	Eucalyptus.	Eucalyptus globulus..	Cal.	.63	3440	22.5	7.6	15.3	79
38a	Oak, cow........	Quercus michauxii. ...	La.	.60	3280	19.4	5.9	9.2	76
38b	Oak, laurel	Quercus laurifolia . ..	La.	.56	3060	19.0	3.9	9.5	85
42a	Oak, Spanish......	Quercus pagodifolia. .	La.	.61	3330	16.4	5.2	10.8	78

TABLE VII.—SHRINKAGE FROM GREEN TO OVEN-DRY CONDITION.—*Continued*

	Species	Botanical name	State	Specific gravity dry wood	Weight per M of kiln dry wood at 5 per cent. moisture 1 inch thick when green	Shrinkage per cent. of green from green to oven-dry			Green moisture per cent. of dry wood
						Volume	Radial	Tangential	
				*	Lbs.				
43a	Oak, water	Quercus nigra	La.	.56	3060	16.4	4.2	9.3	81
43b	Oak, willow	Quercus phellos	La.	.56	3060	18.9	5.0	9.6	94
55	Arbor vitæ	Thuja occidentalis	Wis.	.29	1580	7.0	2.1	4.9	55
56	Cypress, bald	Taxodium distichum	La.	.45	2460	11.5	3.8	6.0	79
57	Fir, Alpine	Abies lasiocarpa	Colo.	.31	1690	9.0	2.5	7.1	47
58	Fir, Douglas	Pseudotsuga taxifolia	Wyom.	.42	2290	10.9	3.7	6.6	32
59	Fir, white	Abies concolor	Cal.	.35	1910	10.2	3.4	7.0	156
60	Hemlock	Tsuga canadensis	Wis.	.34	1860	9.2	2.3	5.0	129
61	Pine, lodgepole	Pinus contorta	Colo.	.37	2020	11.3	4.2	7.1	44
62	Pine, lodgepole	Pinus contorta	Wyom.	.37	2020	10.1	3.6	5.9	58
63	Pine, longleaf	Pinus palustris	La.	.53	2900	12.8	6.0	7.6	63
64	Pine, Norway	Pinus resinosa	Wis.	.44	2400	11.5	4.5	7.2	54
65	Pine, shortleaf	Pinus echinata	La.	.50	2730	12.6	5.1	8.2	52
66	Pine, sugar	Pinus lambertiana	Cal.	.36	1970	8.4	2.9	5.6	123
67	Pine, western yellow	Pinus ponderosa	Ariz.	.35	1910	9.2	4.1	6.4	98
68	Pine, western yellow	Pinus ponderosa	Cal.	.38	2070	11.5	4.3	7.3	125
69	Pine, western yellow	Pinus ponderosa	Colo.	.39	2130	9.9	3.8	5.8	93
70	Pine, white	Pinus strobus	Wis.	.36	1970	7.8	2.2	5.9	74
71	Spruce, Engelmann	Picea engelmanni	Colo.	.33	1800	10.5	3.7	6.9	45
72	Spruce, Engelmann	Picea engelmanni	Colo.	.30	1640	10.3	3.0	6.2	156
73	Spruce, red	Picea rubens	Tenn.	.37	2020	11.8	3.8	7.8	31
74	Tamarack	Larix americana	Wis.	.49	2680	13.6	3.7	7.4	52

* Based on dimensions when green.

more than when dried very quickly in dry air. In fact, the very conditions which are the most suitable for drying the wood without checking are the most unfavorable from the shrinkage standpoint.

In Figure 29 are several boards of *Eucalyptus globulus* and one plank of redwood, all of which were originally the same width, namely, nine inches.

The shrinkages of these pieces from the green to the oven-dry condition were as follows, beginning with the specimen on the right-hand side:

	Per cent.
No. 1.—Redwood, rings diagonal	4.8
No. 6.—San José blue gum, from outer portion of board 3 feet wide	6.2
No. 3.—Piedmont blue gum, *radial,* from outer portion of very wide board	12.3
No. 9.—Piedmont blue gum, *radial cut* from inner portion of board	13.9
No. 2.—Piedmont blue gum, rings diagonal to board	18.7
No. 4.—San José blue gum, *tangential cut*	15.1
No. 8.—Piedmont blue gum, *tangential cut*	23.2
No. 10.—Piedmont blue gum, *tangential cut* (another tree)	23.2

It is thus seen that the shrinkage in the tangential direction is nearly twice that in the radial direction, and that some trees of blue gum shrink very much more than other trees. One remarkable fact in regard to the shrinkage of this species is that, although the shrinkage is phenomenal in *amount,* the *rate* of shrinkage is no faster than that of redwood, but it starts to shrink much sooner, namely, at 80 or 90 per cent. moisture, whereas redwood does not shrink until it has reached 25 per cent. moisture.

The fact that the shrinkage is greater the slower the rate of drying, accentuates the conditions brought about in casehardening, since the outer shell, which dries the quickest, therefore tends to shrink the least, and the inner portion, drying much more slowly, ultimately shrinks the more, thus increasing the internal stresses or the honeycombing.

Shrinkage and "working of wood" can not be eliminated entirely by any known means, although it may be reduced by impregnation with a solution of sugar, known as the "Powellizing Process,"[8] and it may be greatly retarded by a thorough coating of varnish or any moisture-resisting finish. In the Powell process, which is patented, the wood is impregnated with a solution of ordinary sugar, molasses, or beet sugar, about two to two and one-half pounds per gallon, by allowing it to soak in an open tank at 140° for an hour, then raised to the boiling point and boiled one hour for each one inch in thickness, then cooled in five to six hours. It is finally dried and then heated to about 250° F. in order to caramelize the sugar. Sugar, which is a natural product of the cells, being transmutable with cellulose by the living processes, appears to enter into intimate combination with the ultra-microscopic particles which compose the cell walls, in a manner which no other substance is able to do, and it greatly reduces the shrinkage, often to half or even less of

[8] Powell Syndicate, Salisbury House, London Wall, London, E. C.

the normal wood. A thorough coating of varnish will so greatly retard the absorption of moisture from the air or the loss in drying that immediate changes in weather will affect the wood very little. However, it does not remove the difficulty, it only postpones it, and ultimately the wood will shrink or swell, as the case may be, just as much as natural uncoated wood. The same may be said of impregnated wood or wood boiled in oil. Paraffin appears to be one of the most resistant coatings for wood in this regard. Experiment has shown it to be much more effective than linseed oil.

Creosoting wood does not prevent its shrinking and swelling with changes in moisture, but merely retards the action. Wood which has been creosoted will swell just as much as untreated wood. Wood paving blocks which have been creosoted in a dry condition and then laid in the pavements will gradually swell, and if they have been tightly laid, they will inevitably cause the pavement to buckle up. They have been known to exert such a pressure in swelling as to shear off the curb stones.

Only those substances which enter intimately into the cell walls affect the shrinkage. Creosote has been shown to do this to a small extent, and it produces of itself a slight swelling of the wood.

Shrinking and swelling of wood will continue indefinitely with changes in the moisture content in the

air. Although the idea is prevalent that long seasoning reduces this tendency, there is no indication from tests that this is so. Neither do repeated soaking and drying reduce the swelling and shrinking. A white oak beam placed in the roof of "Old South Middle" at Yale University in 1769 was removed in 1907 and tested for strength. A one-half-inch section from the middle of this beam was placed together with two similar pieces of white oak which had air seasoned about a year and left under a shed outdoors for seven months. Both samples were then tested for moisture. The beam contained 12.8 per cent. and the others 13.6 per cent. and 14.1 per cent. respectively. They were then placed in a damp can over water with cover closed for fourteen days, when they had the following respective moisture contents: 26.6, 26.2, 26.4 per cent.

In a cold climate in winter time the air in heated dwellings and buildings becomes excessively dry, even drier than would be considered suitable for a dry kiln. It ranges from 42 per cent. down to perhaps 15 or 20 per cent. In the summer time with no heat on it may frequently rise to 90 or even 100 per cent. humidity, consequently the wood in buildings will continually swell in summer and shrink in winter. If well painted, the doors, floors, woodwork, etc., may continue to shrink in winter for three or four months after the fires are lighted, and will swell in summer as slowly. Thus

these wooden parts will reach their greatest shrinkage in January or February and their greatest swelling in July or August. Observation for six years does not indicate any appreciable reduction in the amount of this "working" with age.

There is, doubtless, however, a subtle advantage in slowly and long seasoned timber, and this consists in the probable gradual reduction in internal stresses, which are brought about by the drying. Wood must be looked upon as a plastic material, and it will gradually give under continuous stresses. From this point of view long seasoned timber should possess certain advantages over quickly dried material, for certain exacting uses as for violins, drawing instruments, fine furniture, etc.

Repeatedly soaking and drying a piece of wood does not reduce its working, as has sometimes been supposed. In fact, it appears to slightly increase the shrinkage, due probably to the gradual leaching out of substances contained in the cell walls. Recent tests made on a number of pieces of mahogany, which were alternately soaked and oven-dried seven times during forty-eight days, gave the following average results:

Total shrinkage first time	4.17 per cent.
Total shrinkage seventh time	4.48 per cent.

Green wood which has been once thoroughly oven-dried does not as a rule quite regain its original dimensions when resoaked.

CHAPTER V

The Principles of Kiln Drying

The drying of lumber is an art which properly combines two distinct problems: One concerns simply the means for evaporating moisture, and the other has to do with the physical conditions involved in the extraction of the moisture from the wood with the least possible injury to the material. In this respect a dry kiln must be considered as something more than an apparatus for evaporating moisture. The second problem has already been discussed in the previous chapter on "How Wood Dries." The first problem will now be taken up in greater detail, with respect to its practical operation or the art of drying. The theories involved in the operation will be treated of in a subsequent chapter on the "Theory of Drying." There are just three factors which the dry kiln engineer has at his disposal in controlling the drying of the lumber, namely, *circulation, relative humidity,* and *temperature.* Circulation is of the first importance because it is the sole means of conveying the heat to the lumber within a pile and for the removal of the evaporated vapor; without it drying on a commercial scale in the ordinary forms of kiln would be impossible. Where there are only a few sticks to be dried it is possible to heat these

by radiation or by direct contact with hot surfaces as in a veneer press, but when a pile of lumber is to be dried, the heat must be conveyed into the interior of the pile by a circulating medium, either air, steam, or other gas. So important is this fact that an entire chapter will be devoted to it. In the case of drying paper the evaporating of the moisture is brought about by direct contact of the sheet with hot iron rolls, or calenders as they are called, and circulation is not necessary. Also in drying veneer, this principle is made use of where the sheets are pressed between hollow iron plates heated by steam. (See Fig. 10.) In the case of lumber, however, these methods are ordinarily impracticable, even though possible, and it is therefore necessary that the air or heating medium circulate through every portion of the pile of lumber. Moreover, the other two factors are entirely dependent upon this one. If the circulation become sluggish at any point, there the temperature will fall and the relative humidity will rise and drying will cease or become very slow.

The humidity is of next importance, because upon it depends the control of the drying operation and the proper condition of the lumber. By a high humidity the surface of the lumber is maintained in a moist condition while the water is being drawn from the center of the stick. Too low a humidity, either at high or low temperature, will generally result in casehardening-

ing, surface checking, and honeycombing. By the humidity in the air the surface is kept in a plastic and suitable condition for the transfusion of moisture through the wood substance. Furthermore, the rate of drying is completely controlled by the humidity. The best humidity will vary greatly with different species, moisture conditions and thickness. In the case of green oak and other dense hardwoods it should be held at 80 or 90 per cent. until the wood has nearly reached its fiber saturation point, and then dropped gradually to about 40 per cent., whereas in the case of green birch or maple, drying may be started at 60 to 65 per cent. and ended at 15 or 20 per cent. Most softwoods may be dried at a relatively low humidity, but some, as western larch and cypress, require almost as high a humidity as oak.

Heat is, of course, the factor which produces the drying. As in the steam engine, the steam and the mechanism are both essential, yet it is the heat which produces the result. It acts in two ways: the heat imparted to the water converts it into vapor, and the higher the temperature the greater is the capacity of the air, or more properly the space, for containing the vapor. Heat also appears to influence the rate of transfusion of the water through the wood substance. The higher its temperature the more rapidly it passes through. The temperature, moreover, has a marked

influence on the physical character of the wood, which becomes more and more soft and plastic, while moist, as its temperature is raised. Strength is greatly reduced with increase in temperature while moist. Here, too, the effect upon different species varies greatly. Some species, as Douglas fir and yellow pine, can be heated to the boiling point without injury and even may be dried at this temperature, while others, as oak, are injured by long exposure to high temperatures and can not be successfully dried under such conditions. A high temperature is not, as a rule, injurious to wood which is nearly dry, although long exposure will cause brittleness. On the other hand, boiling or steaming is not as a rule injurious, providing no drying is allowed to take place at the high temperature. The danger occurs during the first part of the drying. It is very important that the wood be heated clear through to its center before any drying begins, as otherwise surface drying is apt to result, since it has been shown that water tends to move from the hot towards the cold portions of the wood. From the mechanical standpoint, high temperatures are more effective than low for evaporating moisture, but with wood it is the physical requirements of the substance which are the factors determining the temperature.

The principles governing the drying operation may be summarized as follows:

The Process of Drying.—1. The evaporating from the surface of a stick should not exceed the rate at which the moisture transfuses from the interior to the surface.

2. Drying should proceed uniformly at all points, otherwise extra stresses are set up in the wood, causing warping.

3. Heat should penetrate to the interior of the lumber before drying begins.

4. The humidity should be suited to the condition of the wood at the start and reduced in the proper ratio as drying progresses. With wet or green wood it should usually be held uniform at a degree which will prevent the surface from drying below its fiber saturation point until all the free water has evaporated, then gradually reduced to remove the hygroscopic moisture.

5. The temperature should be uniform and as high as the species under treatment will stand without excessive shrinkage, collapse, or checking.

6. Rate of drying should be controlled by the amount of humidity in the air and not by the rate of circulation, which should be made ample at all times.

7. In drying the refractory hardwoods, such as oak, best results are obtained at a comparatively low temperature. In more easily dried hardwoods, such as maple, and some of the more difficult softwoods, as

cypress, the process may be hastened by a higher temperature, but not above the boiling point. In many of the softwoods the rate of drying may be very greatly increased by heating above the boiling point with a large circulation of vapor at atmospheric pressure. In this case the dewpoint should be maintained at 212° F. to prevent surface drying or casehardening.

8. Unequal shrinkage between the exterior and interior portions of the boards and also unequal chemical changes must be guarded against by temperatures and humidities suited to the species in question to prevent subsequent cupping and warping.

9. The degree of dryness attained should conform to the use to which the wood is put.

10. Proper piling of the lumber and weighting to prevent warping are of great importance.

How Lumber Should Be Piled.—In the next chapter the subject of relation of the shape of the pile to the circulation of the air will be discussed in some detail. It is the purpose here to point out how the size and shape of the pile influence both the time of drying and also the way in which the wood dries.

In the first place it should be clearly understood that the *interior* of a pile of lumber can not be heated by radiation, but the heat must be carried into the pile by means of the currents of air passing through the layers of wood. This air will necessarily come in

contact with the outer layers first, to which it will give up some of its heat and through the evaporation it will take on more moisture; consequently, the internal portions of the pile must necessarily lag behind the surface in the rate of drying. Herein is where many designs of dry kilns and drying methods have failed. To dry only a few pieces of wood is a totally different proposition from drying a pile of lumber. What can be accomplished in the case of a small test is often impossible when it comes to a large quantity, owing to the inability of obtaining the conditions in the *inside* of the pile, which are present in the small test.

Furthermore, it should be clearly understood that the *size* of the pile of lumber which can be placed in a kiln is no criterion of the efficiency of the kiln for drying the lumber, in fact, it is more often true that the larger the pile, and the more tightly packed the kiln room, the less efficient is the apparatus. It is not the capacity of the room and the economy of space which should be considered primarily, but the principles upon which the drying depends. Remember always that a dry kiln is a *machine for drying lumber* just as much as a veneer drier is a machine for drying the thin plates of wood, and it is not a *storage warehouse* where economy of space and handling are of the first importance.

In considering the manner in which the air enters

the pile of lumber, there are in general three cases for discussion. First, where the air enters and leaves irregularly at numerous points, a sort of diffusion process. This is what occurs in a loose, flat pile of air-dried lumber when placed in a room with heating coils beneath and no specific form of circulation. This is the slowest system of drying and great variations in temperature and humidity are found to occur at different portions of the pile, but on the whole both sides of the pile dry about alike. It gives better results with air-dried lumber than with green. Second, where the air enters the pile at one side and passes through in a definite direction, leaving at the opposite side. The direction of motion may be horizontal, as in flat, cross-piled lumber in a progressive ventilated kiln, inclined as in the Tiemann kiln, or vertical as in edge-piled lumber. In this case, which is the most definite and positive in its results, the drying is inevitably of a *progressive* nature. The portion of the pile where the air enters necessarily dries first and the portion where it leaves is the last to dry. The air enters the pile at its highest temperature and lowest humidity and leaves the pile at its lowest temperature and highest humidity and the conditions within the pile are progressive from the one to the other. The drop in temperature will vary with the rate of circulation, the *width of the pile,* and the moisture condition

of the wood. This case lends itself most readily to analysis. In fact, from a theoretical analysis of the operation such a pile exactly represents the conditions to which the Table IX, page 245, is directly applicable. Consider a slant pile in the kiln represented in Figure 44, Chapter VIII. The air enters the heating coils at H at temperature t in a saturated condition, is heated to t_2 and humidity h_2 in the flue and leaves the lumber at temperature t_3 and a humidity of h_3. With green lumber and a pile four feet in width with a velocity of circulation so that it requires only two to three seconds for the air to traverse the pile, the drop in temperature will be between 12° to 20° F. at the start with $t_2 = 150°$ to 160°. As the lumber becomes dry the difference between t_2 and t_3 becomes less and less, being about 4° to 6° with t_2 about 170° to 180°, but so long as drying is taking place there will always be a drop.

In a direct comparison between two piles of inch green lumber, one of which was flat, so that the diffusion effect applied and the other inclined with direct circulation, the difference in temperature between the bottom and the center of the flat pile was 57° and in the inclined pile the greatest difference at the same time was only 14°. In the case of large "diffusion" piles of green lumber the difference in temperature may in some cases easily exceed 100° during the beginning of the drying operation.

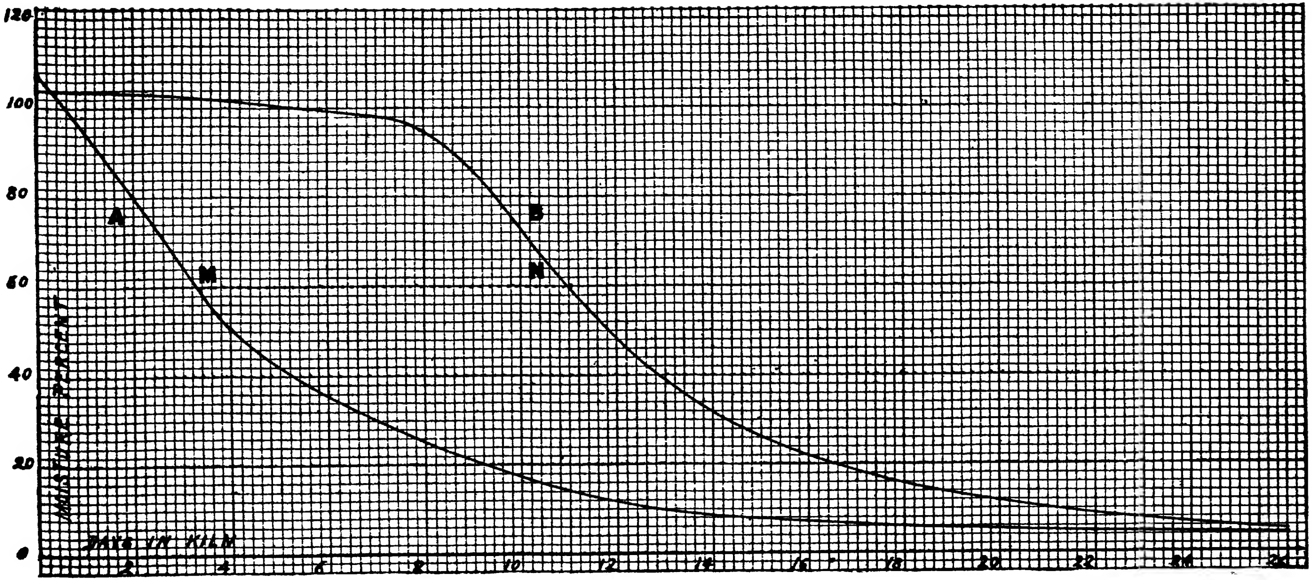

Fig. 30.—Actual drying curves obtained in kiln drying green one-inch red gum lumber in a pile 4 feet wide. *A* is from a board on the entering side, *B* from one on the leaving side. The horizontal distance between the two, *M-N*, represents the *lag* in drying due to width of the pile.

The progressive manner in which the lumber dries in zones throughout the pile in direct circulation is well shown in Figure 30, in which are shown the drying curves for an inclined pile of wet red gum inch lumber, the width being four feet. The curve marked A is for a board on the entering side of the pile and that marked *B* for one on the side where the air left the pile.

The horizontal distance between the two curves *M-N* is, therefore, a factor of the width of the pile. It shows, furthermore, that while it would be possible to dry a few boards on a very narrow pile in the time shown by the curve *A*, the time required to dry any considerable amount of material is increased to that shown by the curve *B*, since it is necessary to retain the entire pile in the kiln until the whole of it is dried to the required amount.

From this it must be very clear that the *length of time of drying is a function of the size of the pile in the direction of the air current.* It is manifestly impossible, therefore, to prescribe a definite time of drying of any species or condition of lumber without taking into consideration the circulation and the size of the pile. The *minimum* time can be stated, however, for a single stick or for the curve *A*.

Furthermore, since variations of 100° or more in temperature sometimes occur with the same pile of lumber, it is manifestly futile to specify the correct

temperatures and humidities for drying lumber without a knowledge of the conditions of drying. Any such statement is misleading or even meaningless.

In the case of the direct circulation system mentioned above, the temperatures and humidities of the *entering* air must be the criterion, since to exceed the requisite conditions at this portion of the pile would cause damage to the lumber. It is not the average conditions which must control the operation, but rather the maximum conditions of the air which comes in contact with the entering side of the pile.

In the drying curves given in Chapter XIII, page 279, it is the temperature and humidity of the air *entering* the pile of lumber which is there specified, for direct circulation. For other methods or forms of piling modifications must be made accordingly.

The third case is where the circulation is reversible; that is, where it first passes through in one direction and then changes and passes through in the opposite direction. Where this can be accomplished in a thorough manner the time of drying will be less than where it is always in one direction, and the two sides of the pile will dry more nearly alike. It is not easy of attainment, however, and arrangements for its accomplishment are more apt to result in the slow diffusion process, with stagnation in portions of the pile.

Drip and Condensation.—When drying at high

humidities, it often happens that the walls of the kiln, and particularly the ceiling, are below the dewpoint temperature of the air inside. Wherever this occurs condensation is certain to take place, popularly called "sweating," and will drip down upon the lumber from the roof or any overhanging parts, causing discoloration, and it may even prevent the drying when it occurs. This is a very disagreeable feature when it occurs on the ceiling. Hence it is of special importance to have the ceiling well insulated and moisture-proof, especially in northern climates. This condensing effect of the ceiling and adjoining portions of the walls may cool the air, in transverse circulating kilns, to such an extent as to greatly retard the drying. For example, suppose the drying temperature to be 160° F. at a humidity of 70 per cent. The dewpoint is then 146°, and unless the ceiling is warmer than 146° condensation will occur.

One means of overcoming this trouble is to suspend a false ceiling about six inches below the ceiling proper. A better method, however, is to run several steam pipes along the ceiling sufficient to raise its temperature to slightly above 146° (in the example given) and the moisture at once disappears. Moreover, this will warm the upper currents of air and assist the drying.

FORM OF THE DRYING CURVE

The drying of a piece of wood under a uniform condition of the air does not occur at a uniform rate, but changes with the amount of moisture contained in

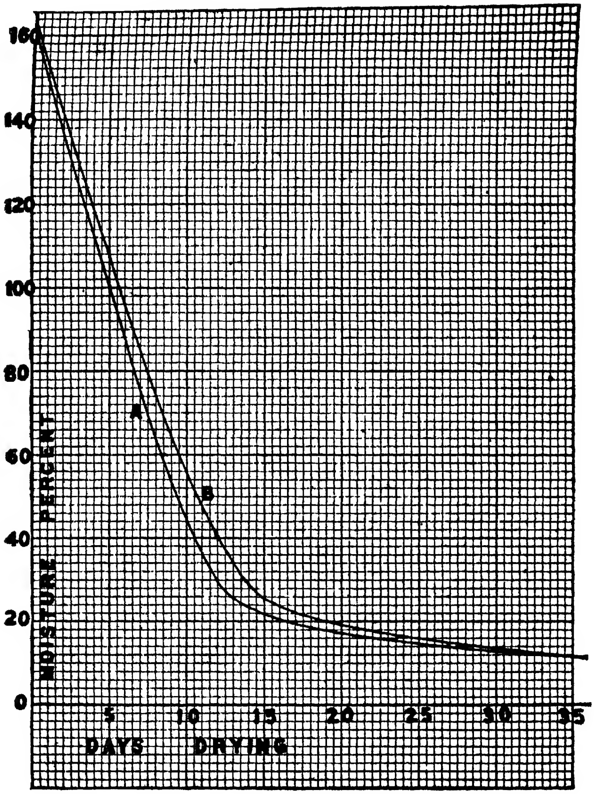

FIG 31.—Air drying curves for two pieces of green western larch sapwood one inch thick, 3 × 3 inches square: *A*, with smooth surfaces; *B*, with rough surfaces. Note the change in rate of drying at the fiber saturation point, 23 per cent. moisture.

the wood. In the case of green wood it is at first relatively rapid so long as there is any free water to evaporate, *i.e.*, above the fiber saturation point. When the fiber saturation point has been reached, however,

there is a marked reduction in the rate, for the hygroscopic water comes off much more slowly. A typical form of drying curve under uniform air conditions is shown in Figure 31, for two pieces of sap western larch. It will be noticed how abruptly the form of the curves changes as soon as the free water has evaporated, *i.e.*, at the fiber saturation point. In order to accomplish the result in a reasonable time, therefore, it is necessary to increase the temperature or reduce the humidity, or both, when the fiber saturation point has been passed. It is important, however, to be sure that the free water has *all* evaporated from the center of the sticks, before the drying conditions are thus greatly augmented, as otherwise the evils of case-hardening will be encountered.

The reason for this change in the rate at which wood dries is evident upon consideration. When it first begins to dry the free water exists in all the pores and cell cavities all the way out to the surface, and the initial evaporation takes place just as from a free surface of water. As soon as the immediate wetness of the wet surface has disappeared further evaporation is hindered by the capillarity and the resistance to the passage of water through the wood. If drying takes place too fast at this point, the continuity of free water between the surface and the interior will be broken, and the rate of transfusion thus retarded.

This is a condition to which the term "casehardening" is often applied. A highly undesirable condition is thus brought about in which the interior of the stick still contains considerable free water, while the surface begins to lose its hygroscopic moisture. It is this *internal free water* which is the most difficult to get rid of, and which is the chief factor wherein the drying of green wood differs from the drying of air-dried wood.

When the free water has finally evaporated, the crucial point in the drying has passed, and there is little danger then of injury to the wood. The most critical point is when the surface has passed the fiber saturation point while the interior still contains some free water; that is, the stage where the greatest injury to the wood is apt to occur, unless conditions are exactly right.

The hygroscopic moisture comes off much more slowly than the free water. As already explained, it can not be "boiled" off. In fact, Dunlap has shown that to separate this hygroscopic moisture from the cell walls requires an appreciable expenditure of heat in addition to the latent heat necessary to vaporize it. This heat of adsorption amounts to about 34 B.t.u. per pound of dry wood at 32° F.

Moisture transfuses through wood much more rapidly in the direction of the medullary rays; that is, radially. Therefore, flat, sawed boards (tangential)

dry more rapidly than "quarter-sawed," "edge-grain" boards (radial). Furthermore, the condition of the surface affects the rate of drying, smoothed surfaces drying the faster. Figure 9 gives the drying curves at living room conditions of two carefully matched pieces of western larch sapwood, one with rough sawed surfaces, and the other planed. It is seen that the smooth surface dries slightly faster than the rough until the wood is nearly dry, when the reverse is the case.

CHAPTER VI

THE CIRCULATION AND THE METHOD OF PILING[1]

As already pointed out, in drying a separate individual stick, the humidity and temperature may be regulated independently of the circulation. When a large quantity of lumber is to be dried, so that it has to be placed in the kiln in the form of a pile, this is not the case. The temperatures and humidities within the pile become dependent to a large extent upon the circulation. A single stick may be heated by radiation from steam pipes or from the wall of the cylinder in which it is placed, but in a pile of lumber the heat must be conveyed to its inner portion by the convection or movement of the surrounding medium. This movement is essential, not only to supply the heat which is required to vaporize the moisture, but to remove the vapor as the air becomes saturated. This conveyance of heat to the inside of the pile and removal of the excessive vapor may occur very slowly through a process of diffusion, as smoke will gradually diffuse itself through a room of perfectly still air, but the process is too slow to be of much assistance in the drying of a pile of lumber.

[1] By permission from the *Lumber World Review*, article by the author.

The extreme slowness of this process of diffusion is evident if a little live steam be let into the top of a closed room of perfectly still air. The lower portion of the room will remain comparatively dry and free from steam, although there is no obstruction to the diffusion of the vapor. Direct conduction of heat is so small an element through the lumber and the air that it is not to be considered. In drying in water vapor alone in the absence of air, as with a vacuum in a closed cylinder or by superheated steam above 212° at pressures of one atmosphere or greater, the object of circulation is merely to supply the heat of vaporization, since the vapor will pass off of itself as rapidly as it is generated. If there were any way of getting heat to the sticks otherwise, circulation of the vapor would not be needed in the absence of air or other gas. For this reason a single stick can be very quickly dried in a vacuum when it can receive its heat by direct radiation, but the case is different in a large pile of material. For the same reason a board can be rapidly dried if placed between two hot plates of metal.

Importance of Circulation.—From the foregoing statements it will be understood why the circulation of the air is of the first importance in the practical drying operations, for it is impossible to obtain correct humidities and temperatures within the pile unless there

be ample circulation in all portions. In fact, it may truthfully be said that *circulation is the keynote to successful drying* on a commercial scale.

Natural Circulation is Downward.—In studying the natural air movement through a pile of moist lumber, it is found that the tendency is for it to descend and not to ascend. This action is caused by the fact that the evaporation taking place cools the air so that it becomes heavier.[2] This increase in density, however, is not quite as self-evident as one might at first conclude, because the additional vapor received from the wood has the opposite effect from the cooling and makes the mixture of air and vapor lighter. However, as shown mathematically, in Chapter X, the combined result of the spontaneous cooling and increase in humidity increases the density sufficiently to cause the air to descend.

This principle, *that the air will spontaneously tend to descend in passing through a pile of moist lumber,* is of great practical significance and plays a more important part than is commonly supposed.

Unless the piles of lumber in the dry kiln are so arranged that the above principle may operate, poor results will almost invariably follow, whether the circulation be produced by condensers, ventilation, or forced draught.

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[2] See Table X.

Piles Constructed with Reference to the General Air Movement.—Another principle of almost equal importance is that the lumber should be piled with reference to the direction of the air motion in the kiln. It should be so arranged that *the path of least resistance lies in the direction of general air movement in the kiln, and that this path should lie in the spaces between adjacent layers of boards.* That is, the stickers should run in the direction of the air current. The boards should not be placed so as to baffle the air currents. Otherwise the air will *short circuit* the piles and not pass through them.

For example, in a progressive kiln in which the air enters at one end and passes out at the other, so that the general movement of the air is in a somewhat horizontal path through the kiln lengthwise, flat piling, crosswise, is a satisfactory method, provided that the boards are spaced sufficiently far apart to allow the air to sink downward at the same time that it moves through the pile. This condition is diagrammatically illustrated in Figure 32, where the ends of the boards are visible in the view, the stickers lying horizontally and lengthwise of the kiln.

Piling Methods Contrasted.—Where the air movement is in a general vertical direction, as is usually the case in compartment kilns, with condensers or with ventilators along the middle or the sides, flat piling

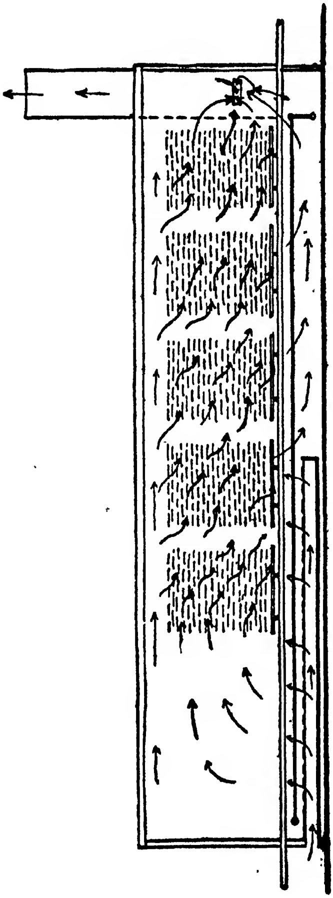

FIG. 32.—Flat crosswise piling is effective when the air currents in the kiln are in the horizontal longitudinal direction. The diagram represents a longitudinal section of a kiln where the air enters through a duct beneath the heaters at one end, and passes out a chimney at the other.

is not at all satisfactory, for the reason that the boards baffle the air currents. An actual test was made with two large kilns, in one of which the motion of the air was lengthwise from end to end, and in the other it was crosswise and vertical. Flat crosswise piling was used in both cases; and although the measured circulation was more than fifty times as great in the kiln with the vertical, transverse movement, the insides of the piles dried no better in the kiln with the enormously in-

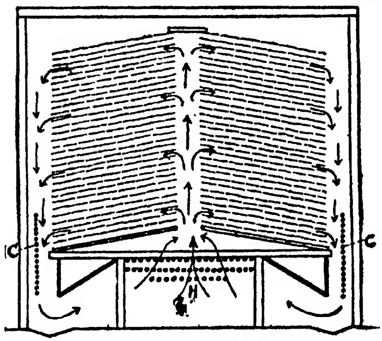

FIG. 33.—Cross section of kiln. Inclined piling is excellent where the circulation is chiefly in the vertical direction and transverse of the kiln. *C*, condensers; *H*, Heaters.

creased circulation. It short-circuited the piles and did not pass through them satisfactorily on account of the baffling effect of the flat piled boards.

Inclined piling, on the other hand, as indicated in Figure 33, or edge-piling, as in Figure 34, gives very satisfactory results with the vertical transverse method of circulation. It will be observed that in Figure 33, which represents a cross section of a condensing kiln,

the lumber is so arranged as to take advantage of the natural tendency of the air to descend in passing through the pile. This is in fact a better arrangement than the edge-piling shown in Figure 34, with heaters beneath the lumber and condensers on the sides, because the forced air movement is contrary to and is opposed by the natural tendency in Figure 34, and local

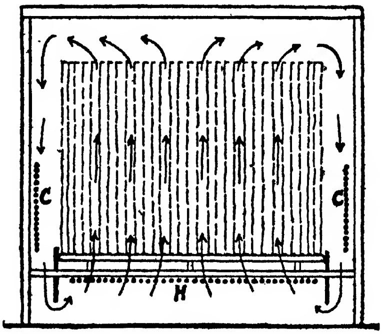

FIG. 34.—Cross section of kiln. Edge piling is effective where circulation is vertical and transverse of the kiln. *H*, heaters; *C*, condensers.

eddy currents are apt to occur, causing stagnation in places and irregular drying.

The Best Arrangement.—The best arrangement of all is that shown in Figure 35 with edge-piled lumber, in which the condensers are placed beneath the pile and the heaters on the sides. This takes the fullest advantage of the principle of descending air and offers the least resistance to its motion. It will give much more uniform drying than the method illustrated in Figure 34, for there is no tendency here for the forma-

tion of eddy currents or stagnation of the air at any point. Both factors are working in the same direction, instead of being opposed to each other as is the case in Figure 34.

By way of caution to those who contemplate erecting new kilns, it should not be overlooked that there are many patents covering kilns which embody in

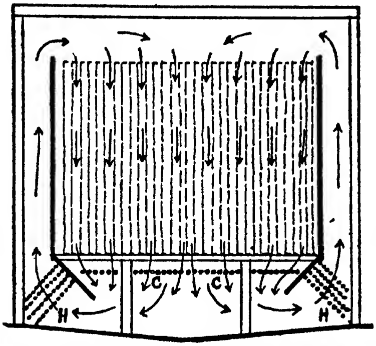

FIG. 35.—Cross section of kiln. The best form of edge piling is where the downward principle is taken advantage of and condensers are below the lumber.

various forms one or more of the methods here discussed. The principles involved, as explained above, have not generally been clearly understood even where they have been utilized to greater or less extent in the patented kilns.

Drying Should Take Place Equally from Opposite Surfaces.—A third principle of considerable importance with certain kinds of sensitive woods is that the drying should take place equally from the opposite surfaces of the boards or shaped blanks. If one surface

dries more rapidly than the other it will shrink less, and a strong tendency to "cup" is produced, the curvature being in a direction away from the surface most rapidly dried. That is to say, the surface which dries most rapidly will be convex. The cause of this will be better understood by referring to the subject of casehardening, Chapter IV. This surface upon which the air impinges casehardens in a stretched condition, while the rest of the block is still wet. Then, as the rest of the block begins to dry very slowly, it shrinks more than this surface, thus causing the block to cup with the casehardened surface on the convex side. On account of this principle it is desirable in the case of sensitive woods that the air shall circulate through the pile of lumber in a direction parallel with the surfaces of the boards and not at right angles to the surfaces. This condition is fulfilled, in all four illustrations given, but is opposed when flat piling is used in transverse-vertical circulating kilns.

If the lumber be dry, or no evaporation be taking place, there will be no downward tendency, unless the temperature of the surrounding air be warmer than that of the pile. It is, therefore, strongest when the lumber is moist and the air is dry.

We will see presently that this observation is correct theoretical reasoning; but before taking up this side of the subject there is another influence to be considered which generally comes into play.

A Cold Pile of Lumber Acts as a Condenser.—When a pile of lumber is first placed in the kiln, it is generally considerably colder than the air in which it is placed. The result is that the pile of cold lumber acts as a condenser of enormous capacity and until it becomes heated through to its normal temperature it will act very powerfully to draw the air downward through itself. This condition is very greatly augmented if the lumber is frozen when placed in the kiln. If anyone is in any way skeptical as to this action, let him crawl beneath a pile of frozen lumber soon after it is placed in the kiln. The downward draught of cold air will be sufficient to remove all doubts whatsoever.

This action takes place with little, if any, diminution, even where the heating pipes are concentrated directly beneath the pile, and condensers are on the side of the kiln (see Fig. 41). Consider the refrigerating capacity of a truck of green maple lumber holding approximately 5000 board feet. The dry wood will weigh about 2800 pounds per thousand, or 14,000 pounds, and it will contain 60 per cent. moisture of the dry weight, or 8400 pounds of water, which is in the form of ice. Over four tons of ice, therefore, must be melted before the lumber can even begin to warm up, or any drying take place. This will require an expenditure of 1,201,200 British thermal units just to

melt the ice alone, without any heating effect. If this must be heated from, say, 32° to 102°, an additional expenditure of 70° times 8400 pounds plus 70° times the specific heat of the dry wood (70 × 8400) plus 70° (14,000 × 0.33) equals 911,400 British thermal units, or a total expenditure of 2,121,000 British thermal units is required before drying begins.

To raise the temperature of one cubic foot of a mixture of saturated vapor and air at 102° and atmospheric pressure one degree, requires 0.01686 B.t.u.,[3] assuming this air and vapor to enter the pile at, say, 122° at 57 per cent. humidity and to cool until it becomes saturated, which will be at 102° (no evaporation taking place, the increase in humidity being due solely to the cooling from 122° to 102°), it will require a minimum of 2,121,000 ÷ (0.01686 × 20°) equals 6,290,036 cubic feet of air (measured at 102°) or 6,513,881 cubic feet (measured at 122°) merely to warm the load of 5000 board feet to 102° without producing any evaporation, assuming all of its heating capacity to be utilized to the maximum amount in passing through the lumber.

As a matter of fact, it would probably require double this amount, since some of it would pass through without parting with all of its heat. This volume of air would occupy a room 20 feet wide by 20 feet high

[3] See Chapter X.

and 15,725 feet, or approximately three miles, long. This is the minimum quantity of air which must come in intimate contact with the lumber under the assumed conditions to warm the pile up to 102° from a frozen condition at 32° before any evaporation takes place.

From this simple illustration some conception may be had of the magnitude of this factor of downward circulation, produced by the coolness of the lumber alone when first placed in the kiln before evaporation begins.

Variations in temperature of the air in the kiln will, of course, influence the motion of the air through the pile. If the kiln is cooling, the condition may be temporarily reversed, since the lumber may then be warmer than the air. When the temperature in the kiln is rising, on the other hand, the conditions may be accentuated.

Temperature of Wet Lumber is Same as Wet Bulb of a Hygrometer.—It has been observed in a previous chapter that the temperature of a wet piece of lumber will be less than that of the surrounding air, except when the air is saturated. While the surface is wet it will, in fact, correspond to the temperature of the wet bulb of a hygrometer. This cooling is due, of course, to the evaporation taking place. When the surrounding air becomes saturated evaporation completely ceases, and the temperature of the wood will gradually rise to that of the saturated air. As the

surface of the wood becomes drier and drier its temperature will gradually rise from that of the wet bulb to that of the dry bulb. When the wood is dry to the point where it is in equilibrium with the relative humidity of the surrounding air, evaporation ceases and its temperature will then become that of the air.

The following experiment illustrates excellently the action explained above which takes place when a piece of frozen, wet wood is first placed in a dry kiln. A stick consisting of a piece of black walnut two and a half inches thick, containing about 50 per cent. moisture, which was frozen clear through, was placed in the dry kiln alongside of a large pile of the same material in position where it received free circulation on all sides. A hole was bored in the center and a glass thermometer inserted and carefully plugged and insulated.

The weights in grammes, temperatures and moisture per cents are given in the table.

Notice that the stick actually increased in weight for the first two and one-quarter hours, and that considerable water condensed upon it in addition and dripped off, which was not included in the weight. Drying did not begin until the stick had been in the kiln for four and one-half hours, and after eight and a quarter hours it was still considerably wetter than when first put in. Comparing the temperature inside

TABLE VIII.—COMPARISON OF TEMPERATURES INSIDE AND OUTSIDE A STICK OF WET WOOD PLACED IN A DRY KILN.

Number of hours in kiln	Weight in grams	Temperatures inside of stick, F°.	Wet bulb F.°	Dry bulb F.°	Hygrometer relative humidity per cent.	Remarks Frozen
0	4004	28	..	..	..	Considerable water dripped off in addition to that weighed.
¾	4040	44	87	93	78	
1¼	4045	60	87	93	78	
1¾	4048	67	87	96	70	
2¼	4050	73	87	96	70	
2¾	4050	75	87	96	70	
3¼	4050	80	87	96	70	
3¾	4050	82	87	96	70	
4¼	4047	84	87	96	70	Drying begins.
4¾	4045	84	87	95	72	
5¼	4042	84	87	95	72	
5¾	4042	84	87	95	72	
6¼	4040	85	88	96	72	
6¾	4038	86	88	96	72	
7¼	4036	87	88	96	72	
7¾	4035	87	88	96	72	
8¼	4031	87	87	95	72	
23¼	3985	90	89	97	73	
25	3978	89	89	97	73	
30	3948	88	87	95	72	
45	3875	97	94	104	69	
50	3855	97	94	106	63	
114	3542	97	92	103	65	

the stick with that of the wet bulb of the hygrometer, it is interesting to see that it required eight and a quarter hours for it to reach the temperature of the wet bulb and that after twenty-five hours they still corresponded.

Precautions in Observing and Determining the Circulation.—The movement of the currents of air is sometimes likened to streams of water in free air. Such a conception is liable to lead to false reasoning and erro-

neous conclusions. A stream of air does not flow in the same sense as a stream of free water in the air does, but it rather floats within itself, being balanced by the surrounding portions, and its motion is brought about by differences in pressure and momentum, instead of directly by gravity, as in falling water.

Differences in pressure may be caused by differences in density, or by mechanical movement of the adjacent portions of air or solid bodies. Until one gets rid of the conception of flowing water it is frequently a surprise to discover the manner in which the air is moving. Hot air does not necessarily ascend unless there is a column of denser cold air to displace it. The actual movement of air through a pile of lumber is sometimes a difficult matter to determine. It is frequently too slow to be measured by an anemometer. Smoke suggests itself, but unless the smoke is of the same temperature as the air, it will give erroneous indications and it must not be given an initial velocity as when blown from the mouth.

I have found that the use of Chinese punk or incense sticks, such as are sold by all druggists for keeping away mosquitoes, is the most satisfactory method. Several of these sticks may be inserted within the pile of lumber, and the movement of the fine threads of smoke observed by an electric hand light. Even in these small sticks, however, there is sufficient heat

at the glowing points to produce a decided initial upward velocity to the smoke, which must always be taken into consideration in making the observations.

Temperature Throughout the Pile an Indication of Circulation.—Another way of determining whether the circulation is sufficient through the pile is by the temperature. If it is sluggish at any point, there the temperature will be considerably lower than normal. In order to determine this, thermometers with stems several feet long are necessary, so that the bulbs can be inserted into the interior. Thermometers with long, flexible tube connections between the bulbs and the indicators are suitable.

To show what this temperature variation may amount to, it will suffice to describe conditions in an experiment in drying inch green maple, already referred to in the last chapter. In this case two piles were placed together in a small compartment kiln, one of which was flat piled and the other inclined, as shown in Figure 33. A curtain was dropped between the two to prevent mixing the air currents and in all respects they were subjected to the same conditions. In the flat pile, however, the boards baffled the circulation and it was sluggish, whereas in the inclined pile it was excellent through all portions. After being in the kiln for nine days, the temperatures in various locations were as follows:

FLAT PILE

Beneath pile	184 degrees
At center of pile	127 degrees
Above pile	158 degrees
Variations between bottom and center	57 degrees

INCLINED PILE

Beneath pile	172 degrees
At center of pile	164 degrees
Above pile	158 degrees
Variations between bottom and center	8 degrees

The inclined pile dried thoroughly and uniformly, whereas the flat pile was covered with mold at the center and not thoroughly dry when both were unloaded at the same time.

Diagrams Showing Circulation Actually Observed in Various Piles.—In order to more fully establish the truth of the principles which have been discussed, a few diagrams will be given showing the circulation as actually observed.

In these diagrams the full arrows indicate the observed circulation and the dotted arrows the probable. The relative rates of the air movements are indicated approximately by the lengths of the arrows.

Figure 36 shows one of three piles of green maple inch lumber of about one thousand feet each, boards edge-stacked, with the stickers running vertically. The heating pipes were below the pile and a condenser chamber on either side of kiln. The top of the par-

tition separating condenser chamber from kiln is shown above the lumber. Notice that in spite of the free open vertical passages the air was descending in some places.

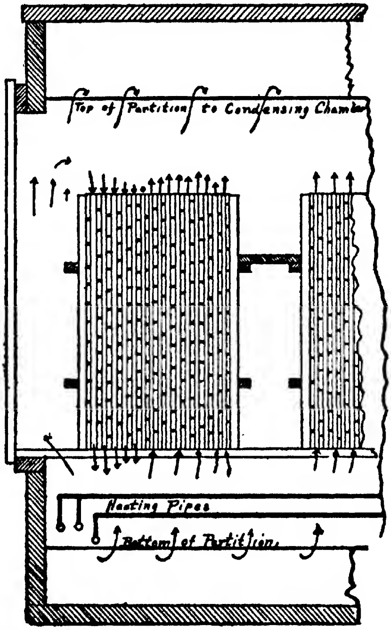

Fig. 36.—Edge-piled lumber. Longitudinal section through kiln. Actual case—note that in spite of the fact that circulation vertically is entirely unrestricted, with heating pipes directly below the pile of lumber and suction above over into the condensing chamber, nevertheless the circulation was downward through the left-hand side of the pile.

Figure 37 shows an inclined pile with the incline in the wrong direction. This was also a pile of green one-inch maple, eight feet high and five feet wide on top and eight feet long. This occupied the same rela-

tive position in the kiln as did that in Figure 36. Notice here that the air is moving in the wrong direction near the top of the pile on one side. The lumber did not dry thoroughly in this position.

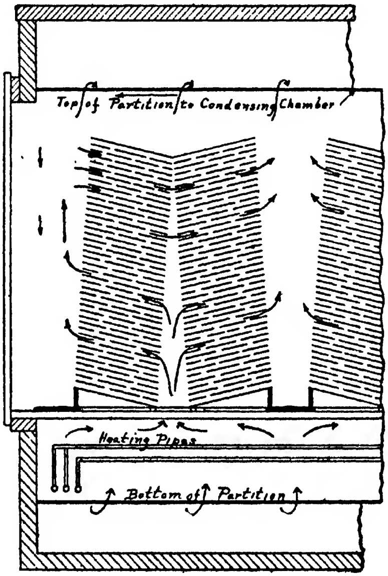

FIG. 37.—Inclined pile of boards, sloped in the wrong direction. Actual case—this is in the same position in the kiln as the edge pile Figure 1. Note that the air is moving in the wrong direction in the upper left-hand portion of the pile.

Figure 38 shows an inclined pile of green inch maple boards which is sloped in the proper direction to take advantage of the descending tendency of the air. This is placed lengthwise of the kiln, a condensing chamber on either side. The circulation here was correct

through all portions and the lumber dried uniformly.

It is possible to so arrange the condensers that they oppose the natural draught and actually retard the circulation, causing stagnation. Such a case is illustrated in Figure 39, in which drying practically ceased, although the humidity above the pile was less than 20 per cent.

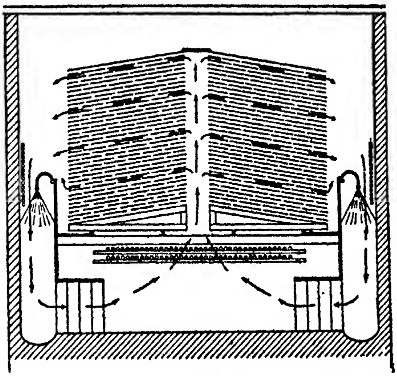

FIG. 38.—Inclined pile of boards correctly sloped. Cross section of kiln. Actual case. Note the excellent circulation.

Example of Downward Circulation in Ventilated Kiln.—A remarkable example of the downward circulation through a pile of lumber in a ventilated kiln of a box form, as indicated by the temperature, is shown in Figure 40. This was a simple wooden kiln about seven feet wide, fourteen feet high, and seventy feet long. A single layer of steam pipes in the bottom on either side of an intake air duct and several stove-

pipe ventilators were placed along the middle of the roof.

The kiln was loaded with green sticks one and one-half inches square by twenty inches long, piled criss-cross, with about one-fourth inch space between. The pile was raised above the rails on 2×8 skids, as shown.

Recording thermometers with long flexible tube con-

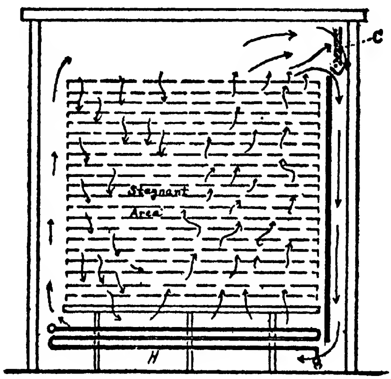

Fig. 39.—Case in which the condenser is so placed as to oppose the natural circulation and cause stagnation in part of the pile. Conditions were improved in this case by entirely closing off the condensing chamber by boarding over the top of the partition just beneath the condenser.

nection to the bulbs were placed in the pile and near roof and sides of kiln as indicated. The lower thermometer A was shielded from direct radiation from the steam pipes by a short piece of inch board, the same length as the bulb, placed beneath it. The readings of these thermometers at periodic intervals are given in the following table:

REFERENCE TO FIG. 40

Days in kiln	A	Thermometer Readings F.° B	C	D	E	
1	60	114	120	119	117	Ventilators closed
2	106	130	133	131	127	Very little steam on in pipes
3	107	113	123	131	114	
4	130	109	114	124	111	Roof ventilators open
8	113	99	122	129	106	Full steam on
10	110	98	123	131	107	
12	110	99	131	134	112	

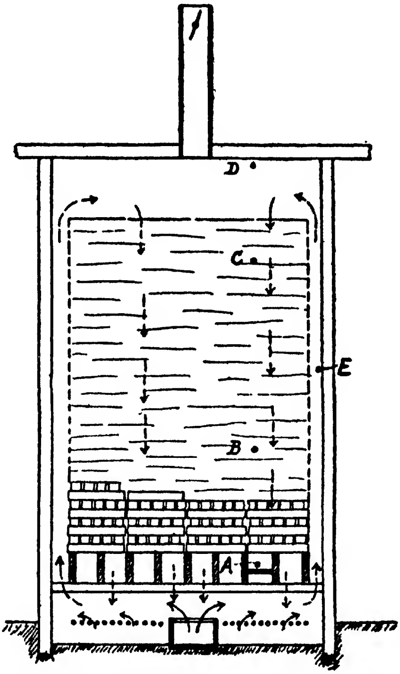

FIG. 40.—Downward circulation in a ventilated kiln observed by temperature measurements and moisture determinations. (See tables.) Note that this kiln was manifestly designed with the idea that the air would pass upwardly through the lumber.

Moisture tests after sixteen days in kiln were as follows:

	Bottom	Middle	Top of pile	
1	44.7	38.6	11.5	per cent. of dry weight.
2	52.4	43.7	13.2	per cent. of dry weight.

It will be seen that in spite of the arrangement being such as to induce an upward movement from the pipes in the bottom to the ventilators in the roof, the progressive drop of temperature from D to C to B shows conclusively a downward movement of air through the pile. Thermometer A beneath the pile was no doubt affected by radiation from the steam pipes.

Forced Draught.—In the case of movement of air by fans or blowers through a pile of lumber, the motion at any point is produced by differential in pressures at that point. Ordinarily the momentum of the air can not be counted upon, since it is broken up by passage through the lumber. Between any two portions of the kiln which differ in pressure *the air will flow along the path of least resistance.* Since the resistance of various portions of the pile must necessarily differ greatly, the velocities of the air will also differ accordingly. In this respect forced draught differs essentially from natural circulation produced by differences in density. The *self-regulatory* feature is also lacking in forced draught. As has been pointed out in the natural cir-

culation, the colder or wetter portions of the pile will automatically draw the greater portion of the air towards them, which is a highly desirable feature.

There is yet another condition which is unfavorable with forced draught. Unless the draught is invariably in the *same direction* as the natural tendency, it will operate against it; and if the two opposing forces happen to balance each other at any point, stagnation must occur and drying is not only not accelerated, but is actually retarded or even prevented at such points by the forced draught. For these reasons forced draught of itself is not apt to give uniform drying, except when it is properly combined with the natural system. If this arrangement can be brought about, however, forced draught may be made of assistance.

Progression of Drying Through the Pile.—Whenever the circulation has a constant direction through a pile of lumber, it follows that the surface where the air enters will dry in advance, and that where the air current leaves, the pile will dry last (Fig. 30). The temperatures and humidities will also be graduated through the pile accordingly, the highest temperature and the lowest humidity being that of the entering air. Suppose the air enters the pile at a temperature of 158° and 13 per cent. humidity and leaves at 75 per cent. humidity. Calculation shows that the air will have cooled spontaneously to 107°, due to the evapora-

tion which occurs. It is evident that the rate of evaporation will be most rapid at the point of incidence and will gradually become less towards the point of exit.

As the lumber nearest the impinging air dries, the evaporation rate will increase progressively through the pile until the most remote portion finally becomes dry. The progress of drying a pile of lumber is there-

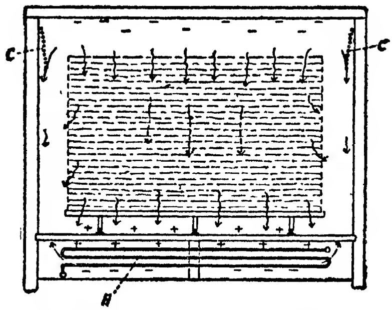

FIG. 41.—Circulation as observed in a pile of cold lumber shortly after being placed in the kiln—note the downward movement in spite of the fact that the heating pipes are directly beneath the pile and condensers are in operation on the two sides. Plus sign (+) indicates motion toward observer, and minus sign (−) away from observer.

fore a progressive one throughout the pile, occurring in successive zones. Therefore, it is fair to conclude that the size of the pile in the direction of the air movement determines the length of time necessary to dry a given lot of lumber, since the load can not be considered ready to be removed from the kiln until the most remote pieces have arrived at the desired degree of dryness.

While conditions in practice will not always agree in detail with the typical case explained above, since there are more often vacillating currents through the pile, the principle must be taken into account in figuring upon the length of time required to dry under given conditions. For this reason it is obviously erroneous to suppose the time of drying in practical operations for a given kind of wood to be a definite quantity, since the form and size of the pile determine the time as well as does the kind of wood.

CHAPTER VII

Special Problems in Drying

Kiln Drying.—Were it not for the unequal shrinkage and the slow rate of transfusion of the moisture from cell to cell, the drying of lumber would present no more difficulty than the drying of wet cloth or clay. The problem would be merely one of conducting the requisite amount of heat to the material to supply that required for vaporization, which at 163° F. is 1000 British thermal units of latent heat plus a small additional amount (about 34 B.t.u. per pound of dry wood)[1] required to overcome the attraction of the hygroscopic material for the moisture. By use of a low pressure or a temperature higher than the boiling point the moisture would pass off directly in proportion to the quantity of heat supplied.

With few exceptions, however, this condition of affairs does not apply in the case of lumber except in the form of thin veneer. The reason for this difference will be made clear in the present chapter.

Properties of the Wood Which Affect Drying.—In the first place let us review the physical properties of the material, which must be recognized in order to intelligently study the drying problem. Different

[1] Frederick Dunlap.

species differ very greatly with respect to the relative proportions of these properties, but all possess them more or less.

1. The rate of transfusion of moisture through the wood substance has already been discussed. It is very slow in some woods, as oak, and fairly rapid in others, as pine. It is supposed that the rate is accelerated by increase in temperature.

2. Wood shrinks differently in different directions, and in different portions of the same piece. Shrinkage usually begins only when the dryness falls below the fiber saturation point, although with some species, as *Eucalyptus globulus* and some oaks, the point is not well defined. It is greatest in the circumferential direction of the tree, being generally twice as great in this direction as in the radial direction. In the longitudinal direction, for most woods, it is almost negligible, being from twenty to over a hundred times as great circumferentially as longitudinally. There is a great variation in different species in this respect. Consequently, it follows from necessity that large internal strains are set up when the wood shrinks, and were it not for its plasticity it would rupture. In some species, such as *Eucalyptus globulus,* the alternate layers of early and late wood of the annual rings shrink very differently in amount, thus causing additional strains and stresses. There is an enormous difference in the total amount

of shrinkage of different species of wood, varying from a shrinkage of only 7 per cent. in volume, based on the green dimensions, in the case of some of the cedars to nearly 50 per cent. in the case of some specimens of *Eucalyptus globulus* and *Eucalyptus viminalis*.

3. Wood substance becomes soft and plastic at high temperature under moist conditions. The effect of temperature upon plasticity varies greatly with different species, some, as western red cedar, redwood and eucalyptus, becoming excessively soft even as low as 150° or 170° F.

4. Cohesion between the fibers easily breaks down with increase in temperature in such woods as western larch and the southern swamp oaks, thus permitting internal stresses to cause checking with great readiness.

5. Tendency to warp is due to a warped direction of the fibers. Cupping of slab cut boards is simply explained by geometrical relations due to unequal shrinkage radially and circumferentially.

6. Wood shrinks more when dried slowly under moist conditions than when dried rapidly. High temperatures under moist conditions are conducive to greater shrinkage.

7. Excessive drying causes brittleness.

8. Wood absorbs or loses moisture in proportion to the relative humidity of the air, irrespective of temperature. This property is known as "hygroscopicity."

9. Hygroscopicity and "working" are reduced but not eliminated by thorough drying.

10. Moisture tends to transfuse from the hot towards the cold portion of the wood.

11. Change of color occurs in some species in drying. This is distinct from sap stain or colors caused by fungus or bacteria. This is notable in hard maple sapwood and in sugar pine. In the maple, a moist, warm atmosphere is conducive to this coloration.

12. Collapse of the cells may occur in some species while the wood is hot and moist. This collapse is distinct from the shrinkage which takes place in the wood substance and is due to a different cause.

13. When the free water in the capillary spaces of the wood fiber is evaporated it follows the laws of evaporation from capillary spaces, except that the passages are not all free passages, and much of the water has to pass out by a process of transfusion through the moist cell walls. These cell walls in the green wood completely surround the cell cavities so that there are no openings large enough to offer a passage to water or air. The well-known "pits" in the cell walls extend through the secondary thickening only and not through the primary walls. This statement applies to the tracheids and parenchyma cells in the conifers (gymnosperms) and to the tracheids, parenchyma cells, and wood fibers in the broad-leaved trees

(angiosperms); the vessels in the latter, however, form open passages except when clogged by ingrowths callec tyloses, and the resin canals in the former sometime form occasional openings. By heating the wood abov the boiling point, corresponding to the external pres sure, the free water passes through the cell walls mor readily.

To remove the moisture from the wood substanc requires heat in addition to the latent heat of evap oration because the molecules of moisture are so in timately associated with the molecules or minute par ticles composing the wood that energy is required t separate them therefrom. Carefully conducted experi ments by Mr. Dunlap show this to be from 16.6 to 19. calories per gramme of dry wood in the case of beec longleaf pine and sugar maple. The difficulty impose in drying, however, is not so much the additional hea required as it is in the rate at which the water trans fuses through the solid wood.

Causes of Various Effects Which Result from Dry ing.—The foregoing facts will account for nearly a the phenomena and troubles which occur in kiln drying

Checking, warping, honeycombing, are due to ur equal shrinkage, crooked grain and casehardening (se Fig. 8). "*Washboarding*" is due to unequal shrinkage c adjacent layers of the annual rings of wood and appear on radially sawed lumber (quarter sawed), Fig. 28

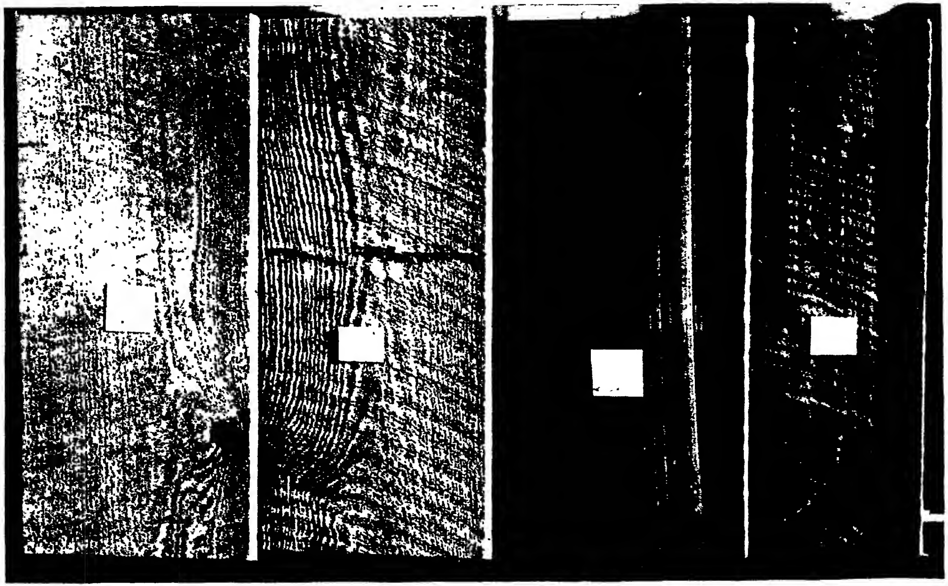

FIG. 42.—Collapse in western red cedar boards. Two specimens on the right show collapse in long streaks in the wet sapwood. Two similar pieces on the left were from the same log, kiln dried so as to avoid collapse.

FIG. 43.—Magnified sections of western red cedar boards, showing the beginning of the "Explosive" effect.

Casehardening has been discussed in the previous chapter.

Discoloring.—It has been found that certain species, as hard maple, change to a cherry color when exposed to very moist conditions at rather high temperature. The very conditions which are best for elimination of checking and casehardening are especially conducive to this coloring. Fortunately, maple, however, does not check easily even in a dry atmosphere, and a temperature of 120° to 125° with a humidity of 50 to 70 per cent. may be used with the green wood, thus avoiding the discoloration. The color appears to be due to an oxidation of a constituent in the sapwood, since it does not occur in the total absence of oxygen. The brown stain, so serious in the case of western sugar pine, may be due to a similar cause.

Collapse of the cells, mentioned under "Properties of the Wood," occurs notably in western red cedar, when the very wet wood is dried at a high temperature. It usually occurs in streaks in the sapwood of the butt log, which is full of water. Fig. 42 shows this collapsed condition in the two boards to the right, and how it was completely overcome by drying at a lower temperature in the similar two boards on the left. This is entirely distinct from the phenomena of shrinkage, and is accounted for by a theory which appears to be borne out by experiments. This is, that the cells

being inclosed capillary spaces and full of water, as the water soaks out through the walls no air can enter and the water exerts a tensile stress sufficient to draw the walls together if they are sufficiently plastic to yield to the stress. It is a well-established fact that water contained in small spaces can exert a tensile stress of cohesion equal to many atmospheres. The solution for the red cedar is to keep the temperature below 135° or 140° so long as the walls are wet. Redwood exhibits a similar phenomenon, and it is probable that it occurs to a modified degree in nearly all woods.

Explosion.—By heating the wet western red cedar above the boiling point, the opposite condition from collapse is brought about—the vapor pressure generated within the non-porous cells forces the walls outwards, and causes the wood to bulge on the surface. The internal condition of an "explosion," as it may be termed, is shown in the section Fig. 43.

Mold.—Mold on the surface of lumber will grow vigorously in a moist or saturated atmosphere at 110° to 130° F. Unfortunately what is the best condition for drying the majority of green hardwoods is the optimum condition for its development. Its growth is checked, however, at 140° F., and 150° to 160° will kill it or prevent further development. This temperature does not sterilize the wood, or render it immune, nor

even 212°, since mold will develop on wood which has been steamed. The main objection to the formation of mold is that it grows across the openings between the layers of lumber and mechanically retards or checks the circulation. It also looks bad. It does not, however, penetrate the lumber or injure it in any way. Dry air will prevent the mold, but is unsuitable for drying green lumber. A temperature above 140°, as stated above, will also prevent it, if the heat can be obtained clear through the pile, but is likewise prejudicial to many kinds of lumber when dried from the green condition. While mold is very often an indication of stagnation of air conditions where it occurs, it is not by any means necessarily so, since it will develop in a high circulation of air if the air is nearly saturated and is at a temperature of 110° to 130°.

A simple means of temporarily alleviating the difficulty, if mold begins to develop seriously, is to steam the lumber at 160° to 180° for half an hour or an hour by injecting live steam into the air through perforated steam pipe suitably placed so as to force the circulation through the pile. This will kill the mold already formed, and it is not likely to develop again. There need be no fear of injuring the lumber by such treatment, at any stage of the drying.

Too long drying at high temperatures even below 212° renders wood brittle and weakens it. Repeated

drying even at 212° gradually changes wood through slow distillation into charcoal. Where the strength of the wood is important, high temperatures must be avoided. In such cases it is unwise to dry the wood much beyond the condition in which it is to be used. Thus, for wagon stock, a dryness of 8 per cent. should be sufficient, if it is uniform, and the material should be allowed to again take up 2 or 3 per cent. moisture in the shed before it is put into the wagon.

The effect of drying on the strength is given in Chapter XI.

Coloring Wood by High Temperatures.—Steaming is sometimes resorted to to darken the color of wood, especially the sapwood, as in the case of black walnut and red gum. The higher the temperature and the longer the exposure the greater is the effect. Steaming at atmospheric pressure for twenty-four to forty-eight hours will considerably darken the color. Steaming under pressure at five pounds for two hours will accomplish excellent results with black walnut, or one and a quarter hours with mahogany. Severe treatment in saturate steam, however, is decidedly detrimental to the strength of the wood, as shown in Chapter XI.

Recent experiments carried on at the Forest Products Laboratory have shown that by treating the perfectly *dry* wood in dry air much higher temperatures can be used with less injury. Red gum is ren-

dered the color of rich dark rosewood by subjecting it to 400° F. for four to six hours. Yellow birch, white ash, and maple are darkened to a pleasing color by the same treatment. Mahogany is greatly darkened to a rich brownish red. The degree of coloring depends upon the temperature used and the length of time of exposure. The wood must be perfectly dry before treatment. An objectionable feature is that it renders the wood more absorptive, and it is difficult to finish, as it absorbs varnish greatly. The coloration is in no wise analogous to a stain, but the effect is produced clear through the board. At the same time the hygroscopicity and consequently the swelling and shrinkage is reduced by about one-half. The wood, however, is made more brittle, although its hardness is not greatly reduced. A loss in bending strength of about 15 per cent. and in work to maximum load (toughness) of about 30 per cent. was found in tests made on this material. In hardness, however, a general reduction of only 9 per cent. was produced by the most severe treatment, and some tests on the maple flooring showed no loss. On black gum the loss was only 5 per cent. A maple floor was laid in which the alternate boards were subjected to this treatment and colored almost as dark as ebony. It has been in constant use. now for a year and shows no greater wear of the treated than the untreated boards. Its applicability to interior trim

and cabinet work, except where brittleness is detrimental, seems promising, except for the cost of treatment. The treatment either in dry air or in steam does not increase the durability of wood either against fungous rot or insect attack, nor is its fire resistance increased thereby.

Darkening wood by fuming with ammonia has been practised for many years. It is generally essential that the wood contain some acids, as tannic acid in oak, in order that the ammonia treatment be effective. Red gum sapwood is stained uniformly brown by ammonia fuming. This is accomplished in ordinary dry kilns. The wood must be thoroughly wet, or must be first steamed until wet. Ammonia gas is then forced into the kiln at the top, which is closed air tight, and is sucked out near the bottom. The fumes are recirculated by a fan. The wood is left in the fumes for several days or longer, according to thickness and the effect desired.

CHAPTER VIII

The Improved Water Spray Humidity Regulated Dry Kiln

It has already been shown that the three fundamental factors necessary in the drying of a pile of lumber are circulation, humidity, and temperature. In an endeavor to produce a commercial kiln in which each of these elements could be regulated independently of the others, the author designed for the United States Forest Service the kiln about to be described. The principle of the forced circulation and humidity control by means of the sprays of water which was the basis of the first patents taken out in 1912 [1] is still the main feature of the present kiln, which has been greatly improved through five years of constant study and experiment, so that the kiln is now well adapted to commercial work. Moreover, the recently discovered principle of the downward circulation through the lumber pile has been taken advantage of in the newest form by so arranging the piles that the air may descend diagonally through them into the spray chamber.

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[1] Patents 1,019,743, March 5, 1912; 1,019,999, March 12, 1912; 963,-832, July 12, 1910; 981,818, January 17, 1911. No. 1,228,989, June 5, 1917. All of these patents are dedicated to the free use of the public.

GENERAL DESCRIPTION OF THE KILN

It is not intended to offer here a working plan or specifications, but merely to give a sufficient description to make its construction and operation plain. For best results, each case should always be worked out to

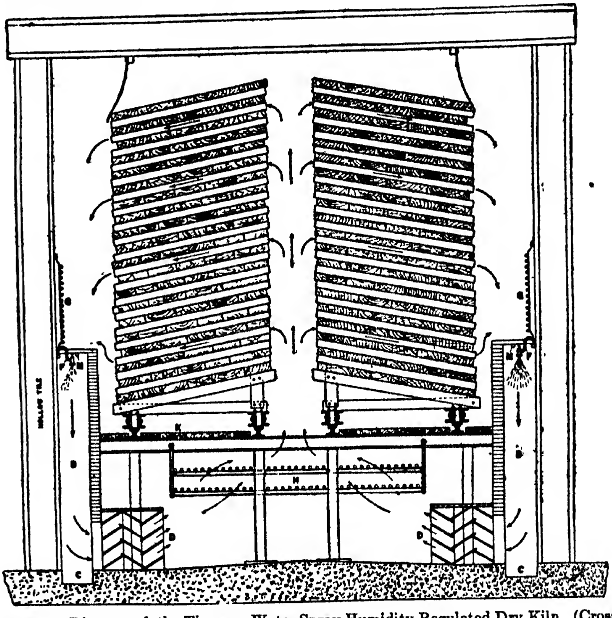

FIG. 44.—Diagram of the Tiemann Water Spray Humidity Regulated Dry Kiln. (Cross sectional elevation.)

suit the particular requirements, and a design made accordingly. For further information the reader is referred to the Forest Products Laboratory, U. S. Forest Service, Madison, Wis., which is conducted in cooperation with the University of Wisconsin.

In Fig. 44 is shown a cross sectional front elevation of this kiln in one of its simplest forms. Spray chambers, *B, B,* are placed on the sides. These are six or seven feet in height, 12 to 16 inches in width, and extend the entire length of the kiln. They are thoroughly waterproofed on the sides. The tops of these flues are open and may be arranged for a footpath or runway. Near the tops are placed the series of sprays, *F, F*. At the bottom are gutters, *C, C,* which drain to the end of the kiln and thence to a well. The bottoms of the flues open into the space beneath the heater coils, but the air is obliged to pass through zigzag baffle plates, *D, D,* which separate all fine mist from the air but allow the air to pass through freely in a saturated condition. These baffles may be made up of boards in convenient sections. Copper nails or wooden dowels should be used. They should fit tightly, as any leakages will allow the spray to get through to the steam pipes, which would spoil the humidity regulation. *H* represents the heating pipes, which are concentrated towards the center. *K* is a floor or shield of loose planks which serves as a bottom to walk on and also shields the lower course of lumber from direct radiation of the heating pipes. The lumber is piled as indicated, with a flue in the middle about 12 inches wide. While the inclined pile as illustrated will give the best results, flat piling, arranged in the same manner with the flue in the

center, will also work well. With inclined piling the boards may be placed solid edge to edge, but with flat piling it is advisable to leave cracks between them so that the air may descend as it cools, passing through in a downward and outward direction. Curtains are hung from the roof to the edges of the piles as shown to prevent the air from passing over the piles and thus "short circuiting" them. Condensing pipes are placed just above the spray chambers at *G, G,* for use at the end of the drying operation when not so great a circulation is needed. Steam sprays are suitably placed beneath the piles for use in removing casehardening. The diagram is drawn to scale for a kiln 13 feet wide, 12½ feet high, and of whatever length desired. Fig. 45 shows the arrangement of this kiln for flat piling.

The water sprays consist of small brass nozzles fitted by means of a one-fourth inch pipe "goose-neck" to the supply pipe as shown. The adjustable "vermorel" type of nozzle, such as is used in horticultural work,[2] which will deliver 2.5 to 3 pounds of water per minute at about 45 pounds pressure, has been found satisfactory. These should be spaced about three feet apart. They should give a *spray* of water and *not* a mist.

The temperature of the water is regulated in a very simple manner as follows:

The water flows by gravity from the gutters into

[2] F. E. Myers, Ashland, Ohio. Graduating Vermorel Spray Nozzles.

a suitable well. From this well it is pumped by a suitable small rotary pump direct to a temperature regulating, mixing valve.[3] Cold water from

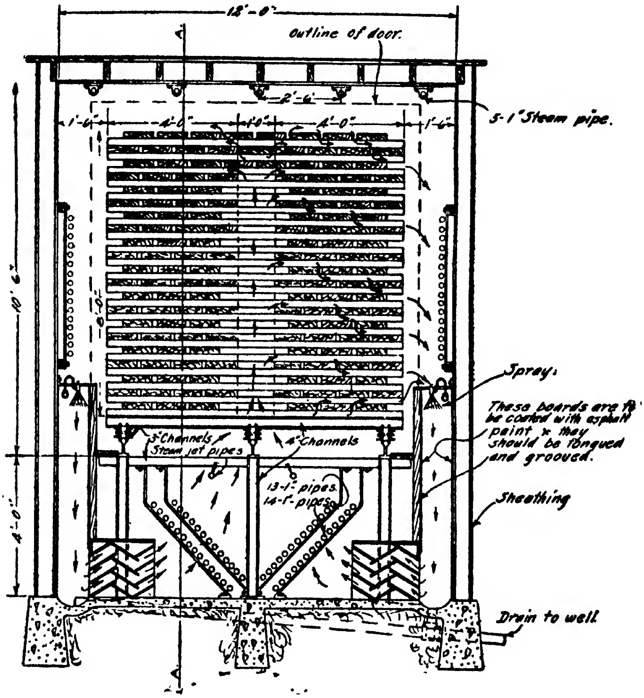

Fig. 45 —Arrangement for flat piling.

the supply main is also tapped into this valve at approximately the same pressure, which should be adjusted to between 30 and 50 pounds. By merely moving

[3] Leonard Valve, Leonard-Rooke Co., Providence, R. I.
Also Powers Regulator Co., Chicago.

a small lever this valve will deliver water at any desired temperature between the two extremes and hold it steady within a degree or two. A steam pipe should also be arranged to discharge into the well for heating the water when very high humidity is called for. A strainer is placed on the water line to prevent the sprays from becoming clogged. Should any one become clogged, however, it can be readily cleaned by its small adjusting screw in the top.

The condensing pipes are also connected to the same circuit through a separate valve from the pipe line leading from the Leonard temperature regulator, so that either sprays or condensers may be operated by the same system by merely opening and closing the respective valves. Fig. 46 shows diagrammatically the arrangement of the spray water and condenser regulating apparatus.

Construction.—Any kind of building construction may be used, but it should be water- and moisture-proof. All cement work except the foundations should be waterproofed. This may be accomplished by using 5 per cent. solution of alum and 8 per cent. of soap in the water used for mixing the concrete, or the walls may be thoroughly coated with high temperature asphaltum varnish.

In cold climates either standard wooden studding construction or hollow tile is preferable on account of insulation. A certain amount of radiation from the

side walls is desirable, since it increases the efficiency of the condensers and the sprays—the heat given to the walls does not need to be removed by the condensers.

Do not use galvanized pipes or metal in a dry kiln, as the fumes rapidly decompose the coating. Use plain wrought iron pipes and paint them with a good high

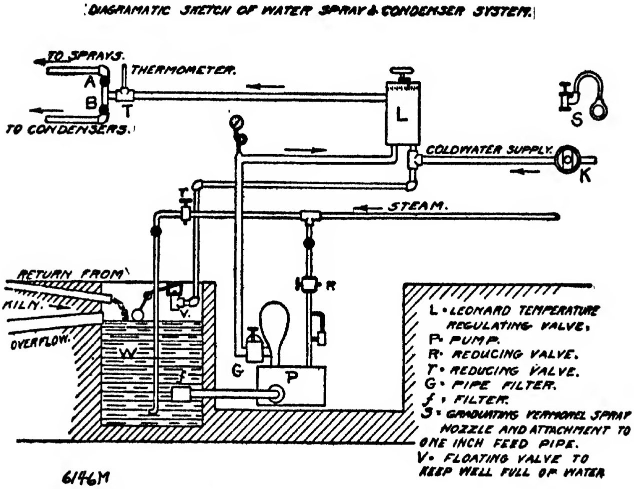

FIG. 46.—Diagrammatic sketch of water spray and condenser system.

temperature asphaltum varnish or black baking japan.

Operation.—The operation is very simple. The heated air rises in the flue between the two piles of lumber. As it comes in contact with the piles, parts of it are cooled and forced to pass outwardly through the piles to the spray chambers. Here the velocity of the descending column of air is greatly augmented by the sprays. It then passes out through the baffle plates

into the space immediately beneath the heaters. Here it is in a saturated condition and its temperature is therefore manifestly the *dewpoint* of the air after it becomes heated in passing through the steam pipes. This may, therefore, be termed the *dewpoint method* of humidity control, since this dewpoint temperature is easily controlled by the temperature of the spray water.

Only two stationary thermometers are necessary for determining the humidity and temperature of the air entering the lumber, and therefore for operating the kiln, one in the baffles at D, which thus records the dewpoint, and the other in the flue between the piles of lumber. No wet bulb is needed, nor any hygrometer. It is very convenient to use the recording type of thermometer [4] having long flexible tubular connection with the bulb, and to have both hands recording on the same dial. By means of the humidity diagram given in Chapter XIV the humidity may thus be quickly determined at any time.

The temperature of the entering air may be controlled by any good form of thermostat,[5] of which there are many on the market, or by means of a reducing valve on the steam line.

This type of kiln requires very little attention when properly operating; once a day, or even once every three days, has proved sufficient.

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[4] Bristol Co., Waterbury, Conn., Gass filled type.

[5] Tagliabue Thermometer Co., Bush Terminal, Brooklyn, N. Y., "Perfect" temperature regulator. Powers Regulator Co., Chicago.

The form of the kiln may be varied from that shown. For instance, a single truck may be used. This form would be represented by dividing the diagram, Fig. 44, vertically into two parts. In another form the spray chamber may be placed in the center and the lumber flat piled or sloped in the opposite direction. The air would then rise next to the side walls and descend in the center. For a separate kiln, however, the form illustrated is preferable, on account of the cooling effect of the outside walls. Ventilation may also be used, which reduces the amount of fresh water required, an outtake flue being placed immediately above the spray chambers and an intake beneath the heating coils.

When drying at high humidities it often happens that the walls and roof of the kiln are cooler than the dewpoint of the air. Wherever this occurs condensation will occur and will drip from the ceiling on to the lumber, causing stain and interfering greatly with the drying. Moreover, the cooling effect upon the air above the pile may become so great as to retard the drying of the upper portion of the pile. The difficulty may be partly overcome by suspending a false ceiling a few inches below the ceiling proper. A better method, however, and one which entirely eliminates both troubles, is to place a few steam pipes along the ceiling, sufficient only to keep its temperature slightly above that of the dewpoint of the air.

CHAPTER IX

Drying by Superheated Steam and at Pressures Other Than Atmospheric

1. *Superheated Steam.*—When there is a great deal of free water in the wood the quickest possible way to get rid of it is merely to heat the material above the boiling point, and it will pass off as rapidly as the necessary heat is supplied. Not so with the hygroscopic moisture or the moisture in the cell walls. This can not be boiled off. Thus wood containing say 60 per cent. moisture may be reduced to 30, or in some cases 25 per cent., as rapidly as heat can be conducted to it, but the evaporation will greatly slow up below the fiber saturation point. Now at atmospheric pressure the boiling point is 212°, and it is necessary to heat the wood to this point before boiling will take place. Exactly the same thing may be accomplished at a lower temperature by reducing the pressure to less than atmospheric. This is sometimes called the "vacuum process" of evaporation, but it differs in no other essential from the boiling process at atmospheric pressure than that it takes place at a lower temperature and lower pressure. A "vacuum" in itself, as we shall see in the chapter on the theory of drying, has no inherent or peculiar efficacy in producing drying. A

dish of water will not evaporate in a vacuum any more than in the atmosphere, but it will boil at a lower temperature. Hence the use of vacuum pans in evaporating milk, to reduce the temperature. The most rapid method of conveying heat to the lumber is by the use of superheated steam, but as soon as it has cooled to the boiling point it can produce no evaporation. A number of kilns have been constructed for the use of superheated steam, both at atmospheric pressure and under a partial vacuum. As mentioned elsewhere, the evaporative capacity of the superheated steam is proportional to the product of the quantity coming in contact with the lumber times the number of degrees it is superheated. Consequently, to produce rapid drying it is necessary to have a high velocity or a high degree of superheat. The chief objections to the use of superheated steam in drying lumber, from the standpoint of the process, are the extreme rapidity with which it parts with its superheat and becomes saturated and the high temperature to which it is necessary to heat the lumber. Owing to the former uneven drying is produced, for that portion of the pile which first comes in contact with the impinging steam dries rapidly, and the other portions of the pile, which receive the cooled steam, do not dry at all, until they, too, receive the superheat after the first portion is dry. By increasing the velocity or reducing the size of the pile this diffi-

culty may be lessened. In regard to the temperature, it is evident that at atmospheric pressure the wood must be heated to 212°. So long as there is plenty of free water present it is impossible to heat the lumber above this temperature, no matter how hot the steam may be, but as soon as the free water has all boiled off, the temperature will begin to rise until ultimately it reaches the temperature of the superheated steam. Some species, such as the western firs, Alaska cedar, and yellow pine, are not seriously injured at this temperature, but the majority of woods, including nearly all the hardwoods, will not stand it. Some of the conifers as western red cedar (*Thuja plicata*) when heated above the boiling point are torn to pieces by the expansion of the steam generated in the cells. Temperatures of 300° F., or more, are in use with superheated steam, which is usually forced into the kiln by means of a blower. The heat may be produced, however, by the heating pipes within the kiln itself.

In the improved method recently developed for the Forest Service * a remarkably low temperature of superheat is made possible by producing a very high velocity of the steam passing through the lumber. The high velocity is produced within the kiln itself by means of steam jets, and the superheating is accomplished by steam heating pipes in the current of steam. Very successful drying has been accomplished with a tem-

* See page 48.

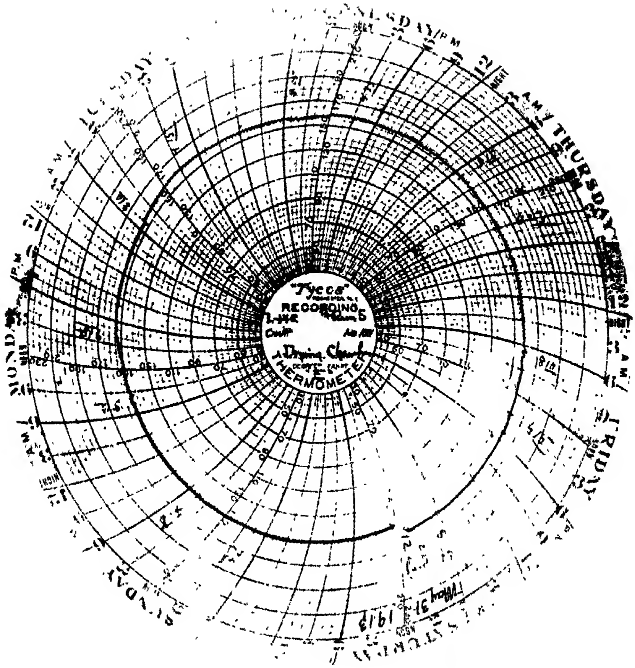

FIG. 47.—Recording thermometer record of temperature of kiln thermostatically controlled.

perature as low as 220° to 225° F. (See Table IV, page 50.)

Application of New Method.—In applying this method, it can be readily combined with my spray-condenser system, by the addition of the water sprays and the pipe condensers in the spray chambers. By this combination, the drying may be hastened towards the end of the operation without necessitating an exces-

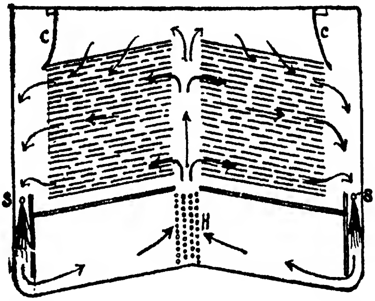

FIG. 48.—Simple arrangement for use of High Velocity Superheated Steam Method with inclined piling system. *S,S*, steam jets. *H*, heating coils. *C,C*, curtains.

sively high temperature to end with. This is desirable also where very dry wood is required.

In the illustrations the water sprays and condensers are not shown. In Fig. 48 the condensers would be placed on the side walls, immediately above the steam jets *S,S*, and the water sprays alongside the steam jet pipe. In Fig. 49 the condensers could be placed beneath the lumber, where the heating pipes are shown. There is no place, however, for the water sprays in this arrangement.

Flat Piling with Reversible Circulation.—The most recent design for the use of this high velocity low superheat method is shown in Fig. 50, in which the lumber is flat piled.[1] The heating pipes are on the sides of the kiln, and an auxiliary system of pipes is placed between the two stacks of lumber to restore the superheat of the steam in its horizontal passage through the lumber. The steam jets are placed in the free passageways both

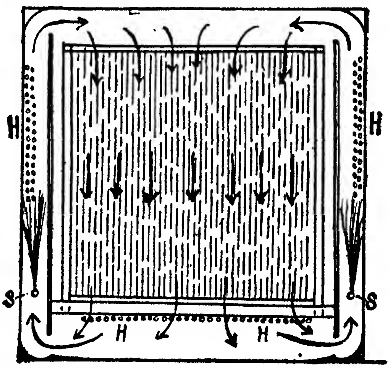

Fig. 49.—Arrangement for use of High Velocity Superheated Steam Method with edge piling system. *S,S*, steam jets. *H,H*, heating coils.

beneath and above the piles. By the use of two sets of jets facing in opposite directions a great advantage is obtained in being able to reverse the direction of the circulation during the drying operation, thus hastening it and producing more uniform results.

Other methods have been tried from time to time, such as placing the lumber in a cylinder lined with heat-

[1] Patent applied for and dedicated to the public for free use.

ing pipes and drawing a vacuum. A small number of boards can be rapidly dried by this method, since they receive heat from the cylinder walls by direct radiation. With a large pile of lumber, however, this is not the case, and it is impracticable to get heat to the inside of the pile, which is consequently very slow in drying. The

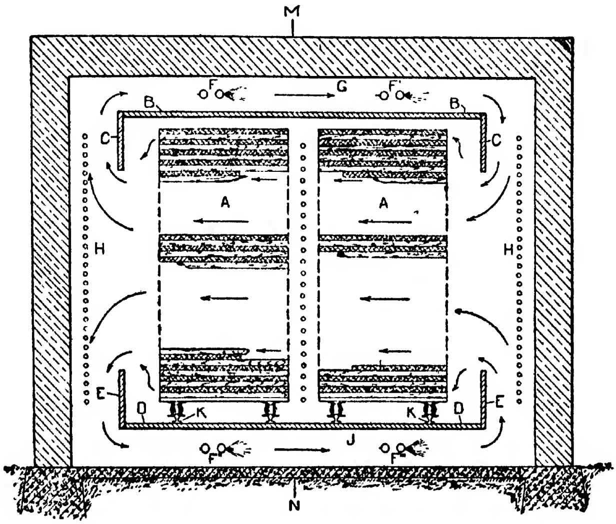

FIG. 50.—Arrangement for use of the New High Velocity Low Superheat Method with flat piled lumber and with reversible circulation.

only advantage the vacuum has is in reducing the boiling temperature of the water in the wood. More heat, however, is required to vaporize water at a low temperature than at a high temperature, as its latent heat is greater. Still another method which has been tried consists in heating the wood in saturated steam, then

drawing a vacuum, again heating in steam, and drawing a vacuum, and thus repeating the operation until the wood has dried to the desired point. The principle upon which this depends is that the specific heat of the wood substance plus that of the water itself contained in the wood after heating in the steam supplies sufficient heat to vaporize a certain amount of water when the vacuum is drawn. When the wood has cooled to the saturation point corresponding to the vacuum pressure, it must again be heated to produce any further drying. The amount which the wood will dry can be readily calculated, if the percentage of moisture it contains is known. Thus, suppose we have 1 pound of dry wood and 50 per cent. or half a pound of water. It is heated to 212°, and a vacuum of 15 inches is drawn (absolute pressure of 15 inches), which corresponds to a boiling point of about 179° Fahrenheit. There is then $212-179 = 33°$ of heat available for evaporation. As the specific heat of wood is 0.33, the total available heat in the pound and a half of wet wood is $(0.33+0.50)\times 33° = 27.39$ heat units, and this is capable of evaporating $\frac{27.39}{969} = 0.0277$ pound of water, or the moisture in the wood will be reduced from 50 per cent. to 47.2 per cent. by one heating and vacuum. A second time it will be reduced accordingly and so on. After a while, however, the absorption during the steaming will equal the loss during the vacuum. It is then possible to continue

the drying by heating in partially humidified air, with sufficient humidity to prevent evaporation during the heating process, followed as before by a vacuum. Theoretically, this system of drying should be as near perfection as it is possible to obtain, because no drying takes place during the heating process, but it is all produced from the self-contained heat only and proceeds from the inside outwardly, the free water being driven from the hot interior to the cooler surface. Instead of drawing a vacuum the same or nearly the same result is accomplished by heating and then exposing to cool dry air. In this case, the operation is also self-regulatory, since those parts receiving the greatest air circulation are cooled more rapidly and evaporation is retarded. Practically, it does not work very satisfactorily, as it requires too long a time to dry and involves too many processes; it is cumbersome to handle. Some woods, as oak, surface check badly by this method along the medullary rays.

2. *Steaming Under Pressure.*—Steaming lumber for various lengths of time under pressures greater than atmospheric has frequently been tried as a preliminary treatment to both kiln drying and air drying. This is usually accomplished in a steel cylinder into which the entire truck load of lumber may be run.

Statements as to results obtained by this treatment are very conflicting. Some claim that green lumber

can be air dried to shipping weight after steaming at 20 pounds for twenty minutes in 30 days, which would otherwise require three months. Others claim that 2-inch black walnut and mahogany can be kiln dried to shipping weight in a dry kiln in two days after steaming at 5 pounds for 2 hours. Again some have had very poor success and have found that it tears the lumber to pieces. Air-dried oak flooring is being handled by this method at 20 pounds for 10 minutes in at least one case with apparent success. In the majority of cases, however, steaming under pressure has been found to be very harmful to oak, due to surface checking, which takes place as soon as the oak is removed from the steam.

Laboratory experiments and actual moisture tests do not bear out all of the claims for this treatment. The great increase in rate of drying has not been found to exist, although a certain advantage in point of time of drying, no doubt, may be obtained in some cases with green wood. The following deductions appear possible concerning the effect of preliminary steaming under pressure:

(1) The wood is heated in the quickest possible time. Air dry wood will take on moisture, but green wood will not, if the lumber pile is arranged so that the condensation may drip off into the bottom of the cylinder.

(2) When removed from the cylinder the self-contained heat of the wood is capable of causing spontaneously the vaporization of a definite amount of moisture. As explained above, in the case of steaming at 212°, take for example green wood containing 50 per cent. moisture, then for each pound of dry wood there is half a pound of water present. Suppose this wood be heated in saturated steam at 20 pounds pressure until it is thoroughly heated through, then taken out in the air and allowed to cool. Its temperature when removed from the cylinder will be 259°, and if it cools to 70° there will be $(1 \times 0.33 + 0.50) \times (259 - 70) = 156.9$ heat units available for evaporating moisture. This is capable of evaporating $156.9 \div 966 = 0.162$ pound of water, or the wood may be reduced from 50 per cent. to nearly 34 per cent. moisture as soon as it cools. This will give quite a start over the unsteamed material. Beyond this there appears to be no gain in rate of drying, the drying curves for steamed and unsteamed wood being nearly identical.

Experiments made on carefully matched blocks of red oak $2 \times 2 \times 6$ inches in size gave the following surprising results:

Steamed 1 hour at 20 pounds the steamed pieces dried faster than the unsteamed.

Steamed 1 hour at 40 pounds the two drying curves were practically identical.

Steamed 1 hour at 60 pounds the steamed pieces dried considerably slower than the unsteamed.

Steamed 1 hour at 80 pounds, the steamed pieces dried decidedly slower than the unsteamed.

A 4-inch disk was sawed across a freshly felled tree of basswood, containing 89 per cent. moisture. This was split in two across the middle, leaving the bark intact on both pieces. Half of it was steamed at 20 pounds for 20 minutes. The two halves were then stood edgewise on a table in a heated laboratory (winter) and weighed daily. The steamed piece took on a little moisture during the steaming, but rapidly lost this and came back to its original condition. The two drying curves were identical for a time, then the steamed piece dried a little less rapidly than the unsteamed. A remarkable fact, however, was observed, namely, that the unsteamed piece developed quantities of small radial surface checks or crackles as soon as it passed 30 per cent. moisture, or about its fiber saturation point, whereas the steamed piece showed scarcely a check even when dried down to considerably below the point where the unsteamed piece began to crackle very badly. The explanation of this appears to be that in the steamed piece the drying took place *from within outwardly,* due to the heat in the interior driving the water from the center to the surface, whereas the unsteamed piece dried most rapidly from the surface,

causing the surface to dry and shrink while the center still contained some free water. Other experiments made on boards of western larch, oak, red gum, indicate no gain in the rate of drying, but a considerable saving in time due to the initial loss produced by the self-contained heat.

(3) There appears to be a decidedly beneficial result in some cases in the distribution of moisture, as explained above, in the case of the basswood disk, during the drying. The internal heat appears to force the moisture from the interior towards the surface, and the boards dry from within outwardly.

(4) Internal stresses are relieved by the high temperature and the wood adjusts itself. Thus crooked boards may be straightened by this treatment if held flat while in the steam.

(5) It is possible that in some cases shrinkage may be reduced due to the relieving of internal stresses in drying, although direct experimental evidence is conflicting in this respect.

(6) The color is darkened, particularly that of the sapwood.

(7) Resins and gums are hardened and rendered less liable to give trouble in finishing the wood, and fungous growth or rot is temporarily killed. There is no evidence, however, that the durability of the wood is increased.

(8) Different species behave very differently. Where good results may be obtained as in red gum, basswood, ash, and many of the softer woods, injury may be done to many of the hard dense woods, as oak and probably black walnut. The oak when removed from the steam almost invariably opens up in innumerable small surface checks along the medullary rays. This is particularly visible on bastard sawed (flat grain) boards. See Fig. 51, which shows a piece of red oak soon after removal from the steam.

(9) The strength of the wood is reduced, depending upon the pressure, length of time exposed in the steam, and the species of wood.

It is commonly said that steaming "opens the pores" of the wood. This is a misleading statement, as microscopic examination shows that no material change is produced in the structure of the wood by the steaming. In the case of woods which contain "tyloses" in the pores or vessels, these cells are still intact after steaming. For example, white oak, which is completely sealed by these ingrowths known as "tyloses" so that air and liquids can not be forced through the green wood, still remains in the same condition after steaming. It is not changed thereby into a wood like red oak, in which the pores are all open in the green log. In the case of gums and resins, the steaming melts and distributes them throughout the wood. Thus the sap-

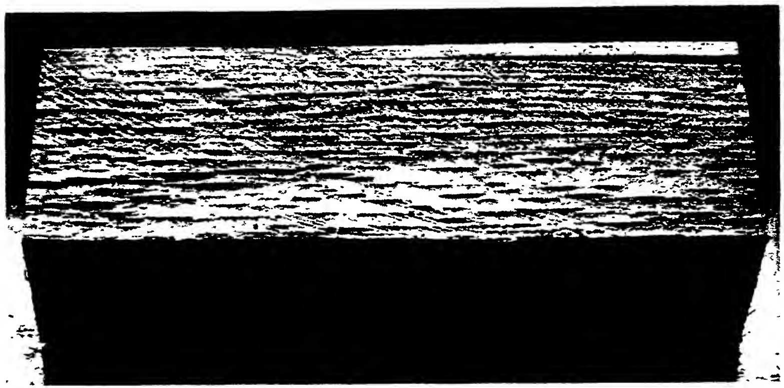

FIG 51.—Block of green red oak after removing from steaming at 212° to 225° for eight hours, showing Medullary Ray Checks on tangential ("Flat grain") surface

wood of yellow pine may be rendered more porous by the melting of the resin from out the resin ducts, and in the case of black walnut the coloring matter is distributed. Chemical changes are brought about in the sap in the sapwood. It is also probable that a partial hydrolysis of the cell walls takes place even at a temperature of 212°. At about 20 pounds gauge pressure, 259° F., a distillation of the wood begins to take place, and acid fumes are given off. At higher temperatures more and more chemical action occurs until finally complete distillation of the wood is brought about.

Steaming will relieve casehardening, as has been explained in Chapter IV, particularly in the case of air-dried wood, by softening the surface and allowing the adjustment of internal stresses to take place. Steaming at temperatures less than 212° is frequently resorted to for this purpose during the progress of kiln drying. When the surface dries so rapidly that the continuity of flow of moisture from the interior to the surface has become interrupted, thus causing a cessation in the rate of drying, it is commonly believed that steaming will start the drying again, by moistening the surface and reëstablishing the continuity. While this theory appears plausible, there are no data available to establish it as a fact.

A carefully conducted research as to the effect of steaming upon the rate of drying, shrinkage, and physi-

cal condition of 2-inch post oak, Biltmore ash, western larch, and Noble fir, both green and air dried, was carried out in 1915 at the Forest Products Laboratory by Mr. J. E. Imrie. Blocks of the various species 2″ × 4″ and 2″ × 6″, 6″ long, and boards 2″ × 4″ and 2″ × 6″ and 30″ long were used, making 120 carefully matched pieces in all. In every case, each treated piece had a counterpart which was air dried without treatment, together with the corresponding piece after treatment. The treatments were as follows:

A steamed 10 minutes at 20 pounds gauge.
B steamed 15 minutes at 0 pound gauge.
C steamed 4 hours at 20 pounds gauge.
D steamed 24 hours at 0 pound gauge.

All pieces were weighed periodically while air drying and their drying rate curves plotted. There is no very marked difference in the rate of the drying between the treated and the untreated specimens, but in some instances there is an immediate loss, which thus reduces the initial moisture content, and if the times required to reach a given moisture condition of 20 per cent. be compared there is a slight gain with most of the steamed pieces. Green oak from treatments C and D reached 20 per cent. moisture in about two-thirds the time required by the unsteamed pieces.

The effect upon the shrinkage is even more erratic: in some cases it was greater, in others less. In the

case of the Biltmore ash shrinkage was reduced in almost every case, but in the green block treatment C it was enormously increased. In post oak the shrinkage was generally increased, except for the air dry boards, in which it was decreased. In western larch it appears to have been somewhat decreased, except in green blocks, and in Noble fir it was increased in the boards.

As to the physical condition, treatments A and B did not harm the green oak boards, and B did not harm the air-dried oak. C and D were very detrimental to oak in checking and warping. A, C, and D injured the air dry oak. In the ash only D caused any degrading. In the larch and the fir the green boards were not injured by any of the treatments, but all of the air dry boards were degraded.

CHAPTER X

Theoretical Considerations and Calculations, Humidity, Evaporation, Density, the Drying Cycle, Amount of Air and Heat Required, Thermal Efficiency

ELEMENTARY PRINCIPLES OF DRYING

Before taking up the theoretical discussion, a few remarks upon the elementary principles of drying will be of assistance.

EVAPORATION REQUIRES HEAT

In the first place, it should be borne in mind that it is the *heat* which produces evaporation and *not* the air nor any mysterious property assigned to a "vacuum." For every pound of water evaporated at ordinary temperatures, approximately one thousand British thermal units of heat are used up or "become latent," as it is called. This is true whether the evaporation takes place in a vacuum or under a heavy air pressure. If this heat is not supplied from an outside source, it must be supplied by the water itself (or the body being dried) and its temperature will consequently fall until the surrounding space becomes saturated with vapor at a pressure corresponding to the temperature which the water has reached; evaporation will then

cease. The pressure of the vapor in a space saturated with water vapor increases rapidly with increase of temperature. At a so-called vacuum of 28 inches, which is about the limit in commercial operations, and in reality signifies an actual pressure of two inches of mercury column, the space will be saturated with vapor at about 101 degrees Fahrenheit. Consequently, no evaporation will take place in such a vacuum unless the water be warmer than 101 degrees, provided there is no air leakage. The qualification in regard to air is necessary to be exact, for the following reason: In any given space the total actual pressure is made up of the combined pressures of all the gases present. Now if the total pressure ("vacuum") is two inches, and there is no air present, it is all produced by the water vapor (which saturates the space at 100 degrees); but if some air is present and the total pressure is still maintained at two inches, then there must be less vapor present, since the air is producing part of the pressure, so that the space is no longer saturated at the given temperature. Consequently, further evaporation may occur, with a corresponding lowering of the temperature of the water until a balance is again reached. Without further explanation it is easy to see that but little water can be evaporated by a vacuum alone, and that the prevalent idea that a vacuum can of itself produce evaporation is a fallacy. If heat be supplied to the

water, either by conduction or radiation, evaporation will take place in direct proportion to amount of heat supplied, so long as pressure is kept down by the pump.

At 30 inches of mercury pressure (one atmosphere) the space becomes saturated with vapor and equilibrium is established at 212 degrees Fahrenheit. If heat be now supplied to the water, however, evaporation will take place in proportion to the amount of heat supplied, so long as the pressure remains that of one atmosphere, just as in the case of the vacuum. Evaporation in this condition where the vapor pressure at the temperature of the water is equal to the gas pressure on the water is what is commonly called by the term of boiling, and the saturated vapor entirely displaces the air. Whenever the space is not saturated with vapor, whether air is present or not, evaporation will take place, by boiling if no air be present or by diffusion under the presence of air, until an equilibrium between temperature and vapor pressure is resumed.

Relative humidity is simply the ratio of the actual vapor pressure present in a given space to the vapor pressure when the space is saturated with vapor at the given temperature. It matters not whether air be present or not. One hundred per cent. humidity means that the space contains all the vapor which it can hold at the given temperature—it is saturated. Thus at 100 per cent. humidity and 212 degrees Fahrenheit the space is

saturated, and since the pressure of saturated vapor at this temperature is one atmosphere, no air can be present under these conditions if open to the atmosphere. If, however, the total pressure at this temperature were 20 pounds (5 pounds gauge), then it would mean that there was 5 pounds air pressure present in addition to the vapor, yet the space would still be saturated at the given temperature. If, however, the temperature were 101 degrees Fahrenheit, the pressure of saturated vapor would then be only one pound, and the additional pressure of 14 pounds, if the total pressure be atmospheric, would be made up of air. In order to have no air present and the space still saturated at 101 degrees, the total pressure must be reduced to one pound by a vacuum pump. Fifty per cent. relative humidity, therefore, signifies that only half the amount of vapor required to saturate the space at the given temperature is present. Thus at 212 degrees temperature the vapor pressure would be only 7½ pounds (vacuum of 15 inches gauge). If the total pressure were atmospheric, then the additional 7½ pounds is simply air. "Live steam" is simply saturated water vapor at a pressure usually above atmospheric. We may just as truly have live steam at pressures less than atmospheric, at a vacuum of 28 inches for instance. Only in the latter case its temperature would be lower, viz., 101 degrees Fahrenheit. Superheated steam is

nothing more than water vapor at a relative humidity less than saturation, but is usually considered at pressures above atmospheric, and in the absence of air. The atmosphere at say 50 per cent. relative humidity really contains superheated steam or vapor, the only difference being that it is at a lower pressure and temperature than we are accustomed to thinking of in speaking of superheated steam, and it has air mixed with it to make up the deficiency in pressure below the atmosphere.

Two things should now be clear: that evaporation is produced by heat and that the presence or absence of air does not influence the *amount* of evaporation. It does influence the *rate* of evaporation, however, as it is retarded by the presence of air. The main things influencing evaporation are: first, the quantity of heat supplied, and, second, the relative humidity of the immediately surrounding space.

IMPORTANCE OF CIRCULATION

A piece of wood may be heated in three ways: (1) By convection of the air and vapor or other gases; (2) by conduction through some body in contact therewith; (3) and by radiation. It is evident upon a little consideration that of these three ways only the first one is ordinarily available for use in heating a pile of lumber, since only the outside surface of the pile could be heated

by the other two methods; hence, the necessity of a large and thorough circulation of air. Drying in a vacuum would be feasible, only providing there were some means of conveying the heat to the wood. A single stick can be readily dried in a vacuum, as it can receive heat on all sides by radiation from the walls of a steam-jacketed cylinder, but this is impracticable when it comes to any quantity of lumber except in the case of superheated vapor alone, as will be shown later, since only the outer surface of the outside boards would receive the heat in this way, and the inside ones would not dry. Thus, by drawing a vacuum the means of heating the wood are reduced. Later on it will be shown, however, that drying at low pressure in absence of air should give the highest theoretical heat efficiency, but the volume of vapor required is excessive.

RATE OF EVAPORATION CONTROLLED BY HUMIDITY

It is essential, therefore, to have an ample supply of heat through the convecting currents of the air. But in the case of wood the rate of evaporation must be controlled, otherwise checking will occur, due to too rapid surface drying, the surface drying more rapidly than the moisture is transmitted through the wood itself. This factor can evidently be completely controlled by means of the *relative humidity*. It is clear now that when the air, or, more properly speaking, the

space, is completely saturated no evaporation can take place at the given temperature. By reducing the humidity evaporation takes place more and more rapidly. Another bad feature of an insufficient and non-uniform supply of heat is that each piece of wood will be heated to the evaporating point on the outer surface, the inside remaining cool until considerable drying has taken place from the surface. Ordinarily in dry kilns high humidity and large circulation of air are antitheses to one another. To obtain the high humidity the circulation is either stopped altogether or greatly reduced, and to reduce the humidity a greater circulation is induced by opening the ventilators or otherwise increasing the draught. This is evidently not good practice, but as a rule unavoidable. The humidity should be raised to check evaporation without reducing the circulation. In the new kiln the humidity is regulated without greatly checking the circulation.

ELEMENTARY PRINCIPLES OF HYGROMETRY

Relative Humidity and Dewpoint.—It is necessary to understand hygrometry in order to get an intelligent idea of drying operations. As stated before, at any given temperature it requires the same quantity of water vapor to saturate a given space whether there be any air present or not, and the pressure of the vapor is the same in both cases. The total pressure (as regis-

tered by the gauge) will not be the same, however, since if air be present its pressure is added to that of the vapor. It is really the space and not the air which is saturated. For instance, at 101 degrees Fahrenheit it takes about 20 grains of vapor to saturate a cubic foot of space. If no air be present there will be a pressure of vapor only, which will be about one pound or a vacuum of 28 inches. If this be open to the atmosphere then the air will rush into the space until the total pressure will be one atmosphere or about 15 pounds. There will then be one pound of pressure produced by the vapor, as before, and 14 pounds of air pressure. The space will still be saturated, if the temperature is kept at 101 degrees. If this be heated now to 160 degrees and open to the atmosphere so that the pressure is kept constant, the ratio of pressures of vapor and air will remain the same; there will still be *one pound due to vapor* and 14 pounds due to the air. (The weights in the cubic foot of space of both, however, will decrease, due to expansion by heat.) At 160 degrees, however, it requires 91 grains of vapor to saturate a cubic foot of space and its pressure is nearly *five pounds* (absolute). Consequently, the relative humidity at 160 degrees of this space will be ⅕ or 20 per cent. Conversely, if this air and vapor at 20 per cent. relative humidity and 160 degrees temperature be cooled to 101 degrees, all at the same atmospheric pressure, the

space will again become saturated and any further cooling will cause precipitation or condensation. This is called the dewpoint, that is, 101 degrees is the dewpoint of air with 20 per cent. humidity at 160 degrees. In Chapter XIV a humidity diagram is given for solving all problems of this nature. The concave curves on this diagram are simply curves of constant vapor pressure with change of temperature and relative humidity, and the grains of vapor per cubic foot, at saturation or the dewpoint, are given in numerical figures. From this it is seen that the dewpoint determines the relative humidity when the temperature is raised, or *vice versa.* If we take saturated air at known temperature and heat it up any given desired amount, the resulting relative humidity is thereby determined. This is the principle upon which the humidity regulation depends in the new kiln designed by the writer.[1] It is also evident that whenever air is cooled below its dewpoint condensation takes place. This is the principle of the condenser. There are a number of kilns which have made use of this principle to dry the air. Pipes are used for the condensers, and cold water is circulated through the pipes. The same thing can be accomplished by a spray of cold water in place of the pipes, provided all the fine mist be subsequently removed from the air, or even by a surface of cold water. In the new kiln a fine spray of

[1] For a description of this kiln see Chapter VIII.

water is used instead of a condenser, which has the additional advantage that when the water is heated above a certain temperature (temperature of the wet bulb in a wet-and-dry-bulb thermometer) it will humidify the air. By simply changing the temperature of the spray the air may be supplied at any desired humidity.

THEORETICAL DISCUSSION OF EVAPORATION

In considering the drying effect of vapor alone (superheated steam) and of air mixed with the vapor, one very significant fact must be noticed. Saturate vapor alone in cooling and in order to remain saturate must *absorb* heat. Its specific heat is *negative*, so that the only way it can impart heat to a body is by condensation. It is, therefore, incapable of producing evaporation. When air is present with the saturate vapor, however, the air can supply some of this heat, according to the pressure of the air present, so there will be less condensation. Still more important is the fact that when air is present with the vapor sufficient heat can be supplied to the body being dried by means of the air without greatly superheating the vapor, thus keeping a high relative humidity and at the same time supplying a sufficient amount of heat to carry on the evaporation. With vapor alone (superheated steam) a relatively high degree of superheating, which means a correspondingly low relative humidity, is required in practice in order to supply the necessary heat for evapo-

ration, after the material has become heated through to the temperature of the saturated vapor at the pressure used. Remember that the temperature of the wet wood corresponds to that of the wet bulb in the hygrometer when air is present, but very nearly to the dewpoint in the presence of superheated vapor alone.

Evaporation in the Absence of Air.—In vapor alone, no air being present, evaporation from a *surface of water* takes place at the dewpoint, but when the water is intimately contained in other substances the temperature must be higher than the dewpoint. If air is present it retards the rate of evaporation from a free surface of water, so that the surface is warmer than the dewpoint, depending upon the degree of relative humidity in the air. In the case of a substance like wood, while its surface is wet its temperature will not rise above that of the wet bulb in the presence of air, nor above the dewpoint in superheated vapor alone. As it becomes drier, however, its temperature will rise, due to its affinity for retaining moisture. In the former condition there is no danger of too rapid drying, but in the latter condition great danger arises, and if the humidity is too low or the superheat is too high the temperature will rise and the drying may become too rapid from the surface so that the moisture is not transmitted from the center as rapidly as it is removed from the surface and casehardening results.

In considering the manner in which drying takes place in superheated steam, it may be looked upon in this way. Suppose the pressure is atmospheric and that a wet piece of wood has been heated in saturated steam to 212 degrees. No evaporation will take place until additional heat be added. Now suppose steam superheated to 232 degrees or 20 degrees of superheat be introduced. The portion immediately in contact with the surface of the wet wood will be cooled to 212 degrees, and in so doing it will vaporize a certain portion of water from the surface. As the specific heat of this steam is, speaking in round terms, one-half, and as it requires about 1000 thermal units to vaporize one unit of water, let us consider a single molecule of water at 212 degrees. To vaporize this molecule of water will therefore require contact of one hundred of the molecules of superheated steam at 232 degrees. We will then have one hundred and one molecules of steam in the saturated condition at 212 degrees, and have evaporated one molecule of water. Evaporation must then cease at this point unless this saturated steam be replaced by some fresh superheated steam. Evaporation from a free surface of water in the absence of air (in superheated steam) always takes place at the boiling point (which in this case is the same as the dew-point). If, however, there is a deficiency of water in the wood, then it requires more heat to separate this water

from the wood and to vaporize it, and the evaporation will take place at a higher temperature than the dew-point. In fact, evaporation may cease altogether in the superheated steam, and a higher degree of superheating be required (which is equivalent to a lower humidity) to get the moisture out of the wood. In the former case of a surface of free water the rate of evaporation depends entirely upon the *amount* of heat transmitted to the water, whether by increasing the circulation or by increasing the degrees of superheat, it matters not, the result is the same. In the latter case, when the moisture is intimately contained in the wood, however, the rate depends largely upon the relative humidity. (In using the term relative humidity as applied to superheated steam, it is understood to mean the ratio of the actual vapor pressure to that of the pressure of saturated vapor at the given temperature, as explained before.) There is a balance between what might be termed the retentive or attractive property of the wood, "hygroscopicity," and the tendency of the moisture to vaporize. It is the difference between the tension of the vapor at the higher temperature of the wood and the tension actually existing in the space surrounding the wood. This retentive property increases as the wood becomes drier and decreases as it approaches the wet condition. Experiments indicate that it is, generally speaking, nearly inversely proportional to

the amount of moisture remaining in the wood.

Evaporation When Air is Present.—When air is present with the superheated steam or water vapor, the conditions are quite different. Vaporization of a particle from the surface of the free water is retarded by the air pressure, so that the temperature of the water may be raised above the dewpoint. (In reality what probably happens is that the layer of air in immediate contact with the water becomes saturated and has a higher vapor pressure corresponding to the temperature of the surface of the water, and the air retards the diffusion of this vapor. The temperature of the water, however, can not, of course, exceed the boiling point for the given pressure, at which point the conditions must become the same as those for superheated steam alone just discussed, since then the air is entirely displaced by the water vapor.)

The air now as well as the vapor conducts heat to the water so that the rate of evaporation at given pressures depends in this case not alone on the *quantity* of heat supplied (by circulation and degrees of superheating), but upon the relative amounts of vapor and air present. That is to say, the lower the relative humidity the greater is the rate of evaporation at a given temperature and pressure.[2] The temperature of the water

[2] The following equation is given by Dr. Julius Hann in his "Lehrbuch der Meteorologie" for the rate of evaporation from a surface of free water:

will correspond to that of the wet bulb and not that of the dewpoint. When the wood becomes partially dried its temperature will rise as in the case of superheated steam, and it may be heated even above the boiling point at the given pressure without giving up all of its moisture, provided there be some vapor in the air.

Conclusion as to Drying in Vapor Alone and in Air and Vapor.—Thus it is seen that in the case of moist air the relative humidity is of prime importance and the rate of drying may be controlled by the relative humidity provided there be sufficient circulation to supply the heat required. In the case of steam alone, the rate of drying as just shown depends upon the *quantity of circulation* as well as the degree of superheating. Hence the conclusion follows that moist air with ample circulation should give more uniform dry-

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$$v = c\ (1 + at)\ (E - e)\ \sqrt{w}.$$

v = velocity of evaporation.
c = constant for any given mean atmospheric pressure B.
c becomes $c\dfrac{B}{b}$ for another barometric pressure b.
a = coëfficient of air expansion.
t = temperature of the air.
E = maximum vapor pressure at the temperature t.
e = actual vapor pressure in the air.
w = velocity of the air over water.

This signifies that, other factors being the same, the rate of evaporation increases inversely with the barometric pressure; inversely as the density at the given temperature; directly as the difference in vapor pressure between that at saturation and the actual pressure present in the air; and directly as the square root of the velocity of the air over the surface.

ing throughout than superheated steam, which varies with the *rate of circulation* in each portion.

But the chief difficulty with superheated steam at or above atmospheric pressure is the high temperatures to which the material must be subjected, the minimum with very wet wood being 212 degrees, and increasing as the wood dries. Below atmospheric temperatures, it is not only costly to construct apparatus for operating at a vacuum, but the heating medium is attenuated, requiring an excessive volume of vapor to be circulated, or else the danger incurred by excessive degree of superheating, that the wood as it becomes dry on the surface will be heated too high, as in the case of steam at atmospheric pressure. Instead of using a vacuum with superheated vapor, the same result so far as the vapor is concerned can be obtained by letting air be combined with the vapor, in which case the air makes up the deficiency of pressure and atmospheric pressure can be used instead of the vacuum. For instance, consider a vacuum of 28 inches, which is about the extreme in mechanical operations; this will give an absolute vapor pressure of about one pound and a temperature of 102 degrees Fahrenheit for saturated conditions. Precisely the same value for the vapor occurs if saturated air at 102 degrees Fahrenheit and atmospheric pressure be used instead, in which case the additional heating capacity of the air present is available

also. There would then be in a cubic foot of space one pound of vapor pressure and 13.7 pounds of dry air pressure. This amount of vapor would weigh 1/334 or .0030 pound, and the air 1/15.2 or .0658 pound (15.2 being the volume of one pound of dry air at 13.7 pounds pressure and 102 degrees temperature).

Heating Capacities of Air and Vapor in Mixture.—The heating capacity of the vapor in this cubic foot of space in falling one degree from 103 degrees to 102 degrees is $.003 \times .42$[3] $= .00126$ B.t.u. as before, while that of the air present is $.0658 \times .237 = 0.156$ B.t.u., or more than *ten times* that of the vapor present. The total heating capacity of one cubic foot of the mixture in falling one degree from 103 degrees to 102 degrees is then the sum of these two, viz., .01686 B.t.u. The latent heat of evaporation at 102 degrees being 1043, it will require the heat given up by $1043/.01686 = 61{,}862$ cubic feet of the mixed air and vapor falling one degree from 103 degrees to saturation at 102 degrees, which is very much less than that required for vapor alone, which, as will be shown further on, is 829,433 cubic feet. In fact, the quantity in volume is less than that of dry air alone at 212 degrees and one atmospheric pressure (69,000) as figured further on. If the vapor be superheated say to 112 degrees, its pressure remaining the

[3] The specific heat of superheated vapor at this temperature is 0.421 as given by Thiesen.

same as before, this is simply equivalent so far as the vapor is concerned to air at atmospheric pressure with a relative humidity of less than saturation. In this case the relative humidity would be the pressure of the actual vapor, one pound, divided by the pressure which the vapor would have if it were saturated at 112 degrees, viz., $1/1.35 = 74$ per cent. humidity.

If the argument has been closely followed it will now be evident that superheated vapor is the same thing as moist air with the air removed. The same effects upon the material to be dried are produced in both cases so far as the vapor is concerned, but in the case of moist air, the effect of the air is added to that of the vapor. The same laws apply to the vapor whether the air is present or absent. The air conveys heat, but by its presence retards the diffusion of the vapor, and consequently retards the rate of evaporation.

Relative Heating Capacities of Air and Vapor Separately.—To compare the relative heating capacities of dry air and of superheated vapor, the following deductions are made: The specific heat of water vapor at a pressure of one atmosphere is .475; that is to say, one pound of superheated steam in falling one degree Fahrenheit gives up 0.475 British thermal unit. To evaporate one pound of water at 212 degrees, therefore, will require the heat given up by 966 (latent heat

at 212 degrees) $\div$ .475 = 2034 pounds of steam falling one degree. At 212 degrees the volume per pound is 26.78 cubic feet; therefore, 2034 $\times$ 26.78 = 54,470 cubic feet of superheated steam falling one degree are required to evaporate one pound of water. The specific heat of dry air is 0.237 and the volume of one pound is 16.93 (.05907 pound per cubic foot) at 212 degrees and atmospheric pressure. Therefore, to evaporate one pound of water at 212 degrees (966 B.t.u.) will require the heat given up by $966 \times \frac{16.93}{.237} = 69{,}000$ cubic feet of dry air falling one degree. It is thus seen that the heating capacity per unit of volume of superheated steam at atmospheric pressure is but little greater than that of dry air at the same temperature and pressure in the ratio of 69,000 to 54,470, or about 5 to 4. At temperatures above 212 degrees and the same pressure of one atmosphere, a greater volume is necessary to produce the same effect, since the gas and vapor expand with temperature, but the ratio of the heating capacity of superheated steam and dry air remains very nearly the same. The specific heat of vapor increases slightly at higher temperatures. Thus figuring in a similar manner it will be found that at 5 atmospheres pressure (59 pounds gauge) the heating ratio of equal volumes of steam and air is 1.42 to 1, and at one pound absolute pressure or a vacuum of 28 inches, it is 1.104 to 1. The volume of steam at 5 atmospheres pressure and

306 degrees Fahrenheit in falling one degree necessary to evaporate one pound of water at this pressure and temperature is 10,336 cubic feet, and at a vacuum of 28 inches at 102 degrees it is 829,433 cubic feet.

Thus it is seen that there is but little advantage from the point of view of the volume of gas to be moved in the use of superheated steam over that of dry air.

In this discussion a cubic foot of space has been used as the basis of the calculations. In analyzing the heat quantities in the drying operation, it will be easier to use one pound of dry air as a basis, with its accompanying moisture, and follow it through its various stages. Its volume will therefore not remain fixed, but will change with every change in temperature and consequently the degree of saturation produced by a definite amount of moisture accompanying it will depend upon the volume which it occupies.

THEORETICAL ANALYSIS OF HEAT QUANTITIES

For this purpose the simplest way will be to follow *a pound of dry air* through a drying cycle as a basis for computations. While in reality the vapor does not enter the air like water in a sponge, but occupies the same *space* whether air be present or not, we may, for convenience, conceive of a pound of air as containing a certain amount of vapor, which, in reality, means that the *space* occupied by a pound of dry air under given conditions contains a certain amount of vapor.

Vapor and Air in Mixture.—As already explained, the total pressure always is the sum of the individual pressures of the air alone plus the vapor alone. Thus, we may speak of a pound of air as being wholly or partially saturated with vapor, meaning that it is the *space* occupied by the pound of air which is in this condition of vapor. If a pound of air said in this sense to be containing a given weight of vapor be heated a given amount under the same pressure of one atmosphere both air and vapor will expand the same amount, so that at the new temperature both will occupy the same amount of space again, which is greater than before, but the pound of air will still contain the same weight of vapor. It would be well to note, however, that the amount of vapor contained in a pound of air alone when it is saturated can not be used as the divisor in obtaining the relative humidity when compared to the amount of vapor actually contained in the pound of air alone, for the reason that when the air is saturated the pressure of the air alone will have been reduced corresponding to the increase in the vapor pressure (since the sum of the two makes up one atmosphere), so that for a pound of air a much greater space is required and consequently an equivalently greater weight of vapor will be occupying this larger space. For relative humidity it is necessary to compare the weights of vapor which occupy the same amount of space when

partially or wholly saturated, or, better still, to compare the *vapor pressures,* since no confusion is then likely to arise.

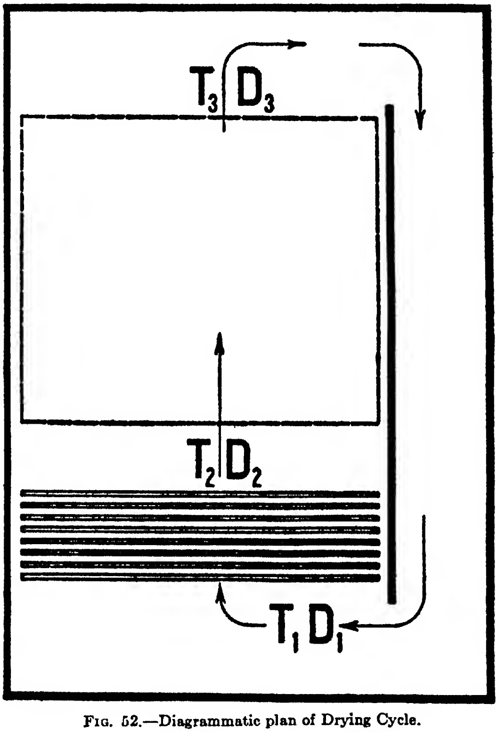


FIG. 52.—Diagrammatic plan of Drying Cycle.

Cycle in Drying Operation of One Pound of Air.—Let us follow the pound of dry air through its cycle of operation: Let the air enter the heater either from outside or from the spray chamber at temperature t_1, and let it contain d_1 pounds of vapor. (See Fig. 52.) Both

the air and the vapor are raised to the temperature t_2 after passing through the heater, each pound of air still contains d_1 pounds of moisture, since the vapor expands the same amount as the air in heating from t_1 to t_2 and both occupy the same volume, which is greater at the higher temperature, d_2 and d_1 are therefore the same so long as no vapor is added or subtracted during the heating from t_1 to t_2. In passing through the lumber, they become cooled to t_3 and an additional amount of moisture w is added from the evaporation so that the pound of air at temperature t_3 now contains $d_3 = d_1 + w$ pounds of moisture. Thence they either escape into the outer air as in a ventilating kiln or pass into the spray chamber where the heat added by the heater and the extra amount of moisture w is removed from the pound of air into the spray water, and it is returned at the initial temperature t_1 saturated to repeat the cycle. The changes in total pressure will be so slight that they may be neglected and the whole operation be considered to take place at a uniform pressure of one atmosphere. Let r equal the specific heat of air at constant pressure and s that of superheated vapor. These will be taken as 0.237 and 0.475 respectively. Then the quantity of heat imparted to the pound of air and its accompanying d_1 pounds of vapor by the heater is (1), $(0.237 + d_1 \times 0.475)\ (t_2 - t_1)$ and the amount of heat given up in evaporating the water

w is (2), $(0.237 + d_1 \times 0.475)\ (t_2 - t_3)$. The amount of water evaporated is $w = (d_3 - d_1)$. Now the heat required to evaporate the water w in continual operation will be that required to raise it from its initial temperature to the evaporating point plus the latent heat of vaporization at this point; also the heat necessary to raise the temperature of the wood alone the same amount. As the latter is small it will be neglected for simplicity. Suppose for a convenient example that the initial temperature of the outside air and of the wet wood be 32° Fahrenheit. Then the heat required is simply the total heat H of w pounds of vapor at the temperature t_3 (nearly).[4] Hence (3), $(0.237 + d_1\ 0.475)\ (t_2 - t_3) = wH = (d_3 - d_1)\ H$ or

$$\frac{t_2 - t_3}{d_2 - d_1} = \frac{H}{0.237 + d_1\ 0.475}$$

In this equation t_2 is a known quantity, being dependent upon the kind and condition of the material being dried. d_1 is known, being the weight of moisture of the outside air per pound of dry air or the weight required to saturate one pound of air in the spray kiln at the temperature t_1. H is known approximately (but not exactly, since its value varies with t_3 or more properly with the wet bulb temperature) and may at first be assumed for some temperature between t_2 and t_1 and afterward be correctly assigned. t_3 and d_3 are the

[4] Evaporation will actually take place at the temperature of the wet bulb if the air is not saturated, after which the vapor is superheated to t_3.

unknown quantities required. If the air is to be considered saturated at t_3, then t_3 and d_3 are dependent variables, their equation being that of the curve of saturation for water vapor. As the equation is complex their relative values can be more readily obtained from a table of saturated vapor and successive values substituted in equation (3) until the equation is fulfilled. Having thus determined t_3 approximately the correct value for H may be inserted and the more exact value of t_3 determined. This has been done by E. Hausbrand in "Drying by Means of Air and Steam"[5] for different temperatures of t_1 and t_2, as well as for different humidities and pressures.

Efficiency of Operation.—With no air present, that is to say with water vapor alone, under a so-called "vacuum" or with "superheated steam" at pressures of one atmosphere or greater, all the heat may be utilized in evaporating the moisture, the leaving and entering temperatures being the same and the pressure constant. With air present, however, and the pressure constant it follows that if the entering air be saturated, the leaving air must be at a higher temperature in order that it may contain the additional vapor at the same pressure. Thus a greater amount of heat is required than that utilized in evaporation, in raising

[5] Translation from the German by Wright. Published by Scott, Greenwood & Sons, 1901.

the temperature of the air leaving the lumber. There is another combination of conditions possible in which the temperature at exit may be the same or even less than that of the entering air or vapor. With air present this is only possible by decreasing the pressure below that of the entering saturated air. In this case, the heat supplied may be even *less* than the theoretical amount required for vaporization, and the theoretical efficiency as reckoned by temperatures is more than 100 per cent., the advantage gained being at the expense of the heat energy in the departing air and vapor, being somewhat analogous to the case of the condenser in a steam engine. The gain in heat is from the fact that the entering air is at a higher temperature than that leaving. If the entering air is not saturated a similar condition is also possible, since some evaporation may take place without necessitating a higher temperature of the leaving air.

From the foregoing it might be concluded that theoretically the use of a vacuum or of superheated steam would be the most economical way in which to dry materials. In the practical working, however, the vacuum has certain disadvantages, as explained heretofore, the chief one being the greater volume of vapor required and the difficulty of producing a uniform circulation of vapor at high attenuation. The other drawback is the expense of the apparatus and difficulty of opera-

tion at pressures other than atmospheric. With superheated steam the temperature is too high for most woods.

Concrete Example of Heat Quantities.—To illustrate the relations of these quantities under the various conditions, let us take a concrete example where the initial temperature of the air is 32° and the air is saturated both at the entrance and upon leaving. This is heated to 158° and then passed through the material to be dried. The volume of the gas required at the temperature of 158° and the theoretically least possible expenditure of heat required to evaporate one pound of water from an initial temperature of 59° Fahrenheit at various pressures are given below.

Absolute pressures	Volume in cu. ft.	Total heat required, B. T. U.
1½ atmospheres	695	2010
1 atmosphere = 760 mm. of mercury	876	1692
500 mm. of mercury, partial vacuum	1247	1578
250 mm. of mercury, partial vacuum	2121	1346
Using steam alone superheated from 140° to 158° at pressure of 148 mm. of mercury, corresponding to saturated conditions at 140° Fahrenheit	16,821	1125

The minimum theoretical expenditure of heat as here calculated has no direct bearing as to the efficiency of any method of drying lumber, however, since the physical requirements of the lumber may, and generally do, demand conditions totally incompatible with the

highest theoretical heat efficiency. They apply directly only to the evaporation of a free body of water, irrespective of length of time required and with no radiation losses. The calculations are useful, however, in showing the limiting values of the efficiency which it is possible to attain under the conditions which have otherwise been found most suitable for drying the lumber in question.

It is instructive to know the highest possible theoretical efficiency in evaporating a pound of water under given conditions, considering no losses in radiation or otherwise. For this purpose the following table (IX) has been worked out, assuming the water to start with an initial temperature of 59° Fahrenheit and to evaporate at the temperature t_3, which is the temperature of the leaving air. The efficiency here expressed is the ratio of the total heat of water vapor at t_3 above 59° divided by the least possible expenditure of heat necessary to evaporate it under the assumed conditions of the entering and leaving air at atmospheric pressure. When the temperature t_1 of the entering air approaches that of the heated air t_2, that is, when a high humidity is used, the calculations become very uncertain, since the quantity of air called for under the assumed conditions approaches infinity, while the temperature differences between t_1 and t_3 become infinitesimal.

The minimum volume of air required to evaporate

one pound of water is also given in table (Table IX).

Generalization.—A study of the theoretical heat relations, as shown by Hausbrand's tables, makes possible the following generalizations:

1. With t_2 constant and entering air saturated, the expenditure of heat is less the higher the temperature t_1 of the entering air.

2. With t_1 constant, the expenditure of heat is less, the higher the temperature t_2 to which the air is heated.

3. Other things being the same, the heat expenditure increases rapidly with reduction in humidity of the emergent air.

4. Other things being the same, the heat expenditure is less, the lower the humidity of the entering air.

5. Other things being the same, the expenditure of heat increases with increase of pressure.

6. With water vapor in the absence of air the theoretical efficiency becomes one hundred per cent.

In regard to the weights and volumes of air required, the following observations are obtained: entering air saturated;

With t_2 constant, both the weights and volumes of air required to evaporate one pound of water increase with increase of the initial temperature t_1 of the entering air.

With t_1 constant, both weights and volumes decrease with increased temperature t_2 of the heated air,

TABLE IX.—MAXIMUM POSSIBLE THEORETICAL HEAT EFFICIENCY OF EVAPORATION UNDER GIVEN CONDITIONS (T_1, T_2, H_1, H_2) AT ATMOSPHERIC PRESSURE (760 MM.)

Entering air		After heating		Leaving air		Heat consumed to evaporate 1 lb. of water, B. t. u. from initial temperature of 59° F.	Total heat of 1 lb. of vapor at t_3 above initial temperature of 59° F.	Minimum volume of air required	Efficiency H÷G
t_1	h_1	t_2	h_2	t_3	h_3				
A	B	C	D	E	F	G	H	J	K
Degrees	*Per cent.*	*Degrees*	*Per cent.*	*Degrees*	*Per cent.*	*B. t. u.*	*B. t. u.*	*cu. ft.*	
32	100	95	11	65	75	2353	1074	2163	.457
59	100	95	31	76	75	2100	1078	3426	.514
32	100	158	2	84	75	1911	1080	993	.565
59	100	158	6	92	75	1715	1082	1126	.631
86	100	158	13	107	75	1556	1087	1402	.698
32	100	212	0+	97	75	1758	1084	694	.617
59	100	212	2	103	75	1572	1086	731	.690
86	100	212	4	114	75	1422	1089	796	.767
32	100	95	11	84	25	6136	1080	5738	.176
32	100	158	2	110	25	2972	1088	1495	.366
86	100	158	13	141	25	4869	1098	4385	.225
32	100	212	0+	126	25	2352	1093	930	.457
86	100	212	4	146	25	2166	1099	1206	.507
32	100	95	11	60	100	1974	1073	1836	.544
59	100	95	31	70	100	1679	1076	2733	.641
86	100	95	74	88	100	1476	1081	9725	.733
32	100	158	2	79	100	1692	1079	876	.636
86	100	158	13	99.5	100	1390	1085	1329	.781
140	100	158	63	140.9	100	1119	1098	3879	.981
32	100	212	0+	90	100	1582	1082	625	.684
86	100	212	4	106	100	1350	1087	721	.804
176	100	212	47	176.5	100	1130	1108	2002	.972
In water vapor alone:									
140	100	158	63	140	100	1097	1097	16418	1.00
212	100	230	71	212	100	1119	1119	3657	1.00
212	100	320	16	212	100	1121	1121	664	1.00

With the emergent air only partially saturated, the weights and volumes increase with decrease of relative humidity in the emergent air.

Conclusion as to Efficiency of Operation.—From this analysis of heat equations the following conclusions as regards the efficiency of the drying may be drawn:

1. The air should be heated to the highest temperature compatible with the nature of material to be dried.

2. The air upon leaving the apparatus should be as near saturation as practicable.

3. The temperature of the entering air should be as high as possible.

Application of Analysis to Water Spray or Condenser Kiln.—The above deductions apply to any form of moist air kiln. The following have more especially to do with our water spray humidity regulated kiln.

The amount of heat absorbed by the spray water and the condensed moisture is the difference between the total heat in the saturated air as it leaves the lumber at t_3 and the total heat in the air at t_1. It is, in fact, the amount of heat given up by the coils, since the air is brought back to its initial state in the cycle and the water evaporated from the wood is added to the spray water. Hence the amount of heat removed in water at a temperature t_1 is (4), $G\ (t_2 - t_1) \times (r + sd_1)$, when G is the weight of dry air in the mixture required to evaporate one pound of water. r is the specific heat

of dry air and s that of the water vapor at constant pressure. Of this the amount $G.\ (t_3 - t_1)\ (r + sd_1)$ represents the loss not accounted for in the latent heat of the pound of water which has been evaporated and is taken up by the spray water. The maximum possible thermal efficiency is therefore

(5) $\frac{(t_2 - t_3)}{(t_2 - t_1)}$ on the condition that just enough air is circulating to give up all its available heat to the evaporation of the water so that it leaves the lumber in a saturated condition. From equation (2) and (3) the value of t_3 is determined for any given values of t_1 and t_2. These values may be most readily obtained from the tables given by Hausbrand, referred to above. t_1 and t_2 are arbitrary values determined entirely by the physical conditions of the material to be dried.

In actual operation, however, the efficiency will be much less than this maximum, since the air leaving will not be saturated and a much larger quantity of air will need to pass through the material than the minimum indicated by this equation. If no evaporation takes place all the heat will be used in heating and cooling the circulating medium. The total heat used per pound of air will then be $(t_2 - t_1)\ (r + sd_1)$ and this will go simply to heating the spray water.

Comparison of Efficiency.—Comparing the efficiency of this kiln with that of the ventilating type, it will be seen that under identical running conditions its effi-

ciency is much greater because the initial temperature t_1 is very much higher. Let the temperature of the outside air be 32°, so that the water has to be raised from 32° to the temperature of evaporation and then evaporated. Let the air leaving the lumber be three-quarters saturated, 75 per cent. humidity. Also let $t_1 = 113°$ and $t_2 = 140°$, giving a relative humidity of 48 per cent. Then d_1 for one pound of saturated air at 113° is 0.0653 pound. Substituting these values in equation (3) to find t_3 and after several trial balances of the values of d_3 at 75 per cent. humidity, these values are found to be $t_3 = 125°$ and $d_3 = 0.06889$. Since $w = d_3 - d_1$, the number of pounds of air required to evaporate one pound of water is $G = \frac{1}{W} = \frac{1}{d_3 - d_1} = 279$, which contains $279 \times 0.0653 = 18.2$ pounds of vapor. The pressure of the saturated vapor alone at 113 degrees is 71.4 mm. of mercury; hence, that of the air alone is $760 - 71.4 = 688.6$ mm. of mercury. The volume occupied by one pound of dry air at 113° and a pressure of 688.6 mm. of mercury is 16 cubic feet (more exactly 15.921), which must be the same as that occupied by the 0.0654 pound of vapor present in the pound of air. As 279 pounds of air are required, with its inherent 18.2 pounds of vapor, the *volume* of air or combined air and vapor is $15.921 \times 279 = 4442$ cubic feet at 113°. At 125° this will occupy 4535 cubic feet.

The total heat consumed is 279 (0.237 + 0.0653

$\times$ 0.475) $\times$ (140—113) = 2019 B.t.u., of which the useful work has been the total latent heat of one pound of vapor above 32° evaporated at 116° (the wet-bulb temperature) and superheated to 125° = 1122 B.t.u. This should be the same as the heat given out by the air and superheated vapor in cooling from 140° to 125°, 279 (0.237 + 0.0653 $\times$ 0.475) (140 — 125) = 1122. The thermal efficiency is $\frac{t_2 - t_3}{t_2 - t_1} = \frac{140 - 125}{140 - 113} = 55.6$ per cent. Also $\frac{1122}{2019} = 55.6$ per cent.[6]

Compare this now first with a ventilating kiln in which the air enters saturated at 32°, is heated to 140°

[6] Another way of arriving at this result is to compare the total heats; thus, in the vapor at 125° and 75 per cent. saturation:

Total heat in the air alone at 125° = 279 $\times$ .237 (125—32)	6,149
Total heat in saturate vapor at the dewpoint of 115° (75 per cent. humidity at 125°) = 279 $\times$ .06889 $\times$ 1117	21,491
Superheating this vapor from its dewpoint of 115° to 125° = 279 $\times$ .06889 $\times$ .475 $\times$ 10............	91
Total at 125 degrees.........................	27,731
At the initial stage 113 degrees:	
Total heat in air = 279 $\times$ .237 (113—32).........	5,356
Total heat in saturate vapor at 113 degrees = 279 $\times$ .0653 $\times$ 1116.4	20,339
Total heat at 113 degrees.....................	25,695

The difference, 27,731 — 25,695 = 2,036 B.t.u., is the heat added to the air. This should be the same as before, namely, 2,019, the difference being in inaccuracy of the constants used.

and leaves at 75 per cent. humidity, escaping to the outer air. We then have:

$t_1 = 32$ degrees, $d_1 = .00387$ pound per pound of air
$t_2 = 140$ degrees
$t_3 =$ calculated $= 80.2$, and d_3 at 75 per cent. humidity $= .01692$

The quantity of air required to evaporate one pound of water is:

$$G = \frac{.01692 - .00387}{1} = 76.6 \text{ pounds}$$

This air contains $76.6 \times 0.00387 = 0.296$ pound of vapor. The total heat consumed is:

$$76.6\ (.237 + .00387 \times .475)\ (140-32) = 1{,}969 \text{ B. t. u.}$$

The thermal efficiency is $\frac{140-80}{140-32} = 55.6$ per cent., which happens to be the same as in our kiln, but examination will show at once that the two cases are not analogous. In our kiln the humidity after heating to 140° was 48 per cent.; in the other kiln it is only 3 per cent., an extremely low amount.

In order to compare the two cases correctly the condition of the air entering the lumber should be the same in both cases; namely, it is necessary to raise the humidity in the ventilating kiln from 3 per cent. to 48 per cent. This can be done by allowing live steam to escape into the heated air sufficient to saturate it at 113°, as this is the dewpoint for 48 per cent. humidity. Now if one pound of dry air saturated at 32° be heated to 113°, it will still contain its original weight of vapor; namely, 0.00387 pound, but to saturate a pound of air at 113° requires 0.0653 pound of vapor; consequently,

the difference between this and 0.00387 or 0.06143 pound of vapor must be added for each pound of air at 113° in order to make the two cases comparable; they are then exactly alike, and we shall have for our kiln, to recapitulate, as before:

$t_1 = 113°$ saturated
$t_2 = 140°$ humidity 48 per cent.
$t_3 = 125°$ humidity 75 per cent.
Number of pounds of air required to evaporate one pound of water at 115° from initial temperature of $32° = 279$
Total heat required $= 2{,}019$ B.t.u.
Heat lost,[7] $2{,}019 - 1.122 = 0.897$ B.t.u.

In the ventilating kiln, on the other hand, we shall have by comparison: $t_1 = 32°$ saturated; $t_2 = 140°$ at 3 per cent. humidity; $t_3 = 125°$, humidity 75 per cent.; h_2 = heat in vapor added to raise the humidity to saturation at 113°; 0.0614 pound is required per pound of air. The total heat in saturate vapor at 113° above $32° = 1117$ B.t.u. per pound; $1117 \times 0.0614 = 68.58$ B.t.u. required per pound of air. There are 279 pounds of dry air required as in the other case. $68.58 \times 279 = 19{,}134$ B.t.u., which must be added as vapor.

K_2 = heat required to raise temperature of the air and vapor from 32° to $113° = 279\ (0.237 + 0.00387 \times 0.475)\ (113° - 32°) = 5396$ B.t.u.

[7] In the spray kiln this is not in reality lost, since part is utilized in producing the circulation and all the remainder is recovered in the spray water. It is simply a transfer of heat from lumber to spray water.

Therefore, in this case, the total heat which must be given to the air to evaporate one pound of water is:

Heat given by coils to raise the air from 32° to 113° = ...	5,396 B. t. u.
Heat given by coils to raise saturate air from 113° to 140° as before = ...	2,019 B. t. u.
Heat supplied in vapor = ...	19,134 B. t. u.
Total heat required = ...	26,549 B. t. u.

Heat lost (provided it all escapes to the air) 26,549 — 1,122 = 25,427 *B. t. u.*

Compared to the loss in our kiln as just shown of only 897 B.t.u., this would be enormous. It would mean an efficiency of only $\frac{1112}{25427} = 4.41$ per cent. The assumption, however, that it all escapes to the outside air is not carried out in practice in the moist air kilns, but instead, a large proportion of this is returned by internal circulation and only a small amount escapes into the air. It is not possible in the latter case to calculate the theoretical efficiency, since there is no means of knowing what portion of the heat is returned in the recirculation within the kiln. The analysis is instructive, however, in showing what enormous heat losses are possible in a ventilating kiln, and the particular object is in showing that in no case can the efficiency of the ventilating equal that of our kiln when operating under *identical* conditions within the drying chamber.

Tendency of Air to Descend Through a Pile of Wet

Lumber.—The method of piling which gives the best results is such that the heated air passes through the pile in a somewhat downward direction; the natural tendency of the cooled air to descend is thus taken advantage of in assisting the circulation in the kiln. This is especially important when cold or green lumber is first introduced into the kiln. But even when the lumber has become warmed the cooling due to the evaporation increases the density of the mixture of the air and vapor. In Table X it is shown analytically

TABLE X.—INCREASE IN DENSITY OF MIXTURE OF AIR AND VAPOR PRODUCED BY THE SPONTANEOUS COOLING OF THE MIXTURE FROM THE EVAPORATION OF MOISTURE AS IT PASSES THROUGH THE LUMBER.

The weights are given in grammes per cubic centimeter of the mixture. The independent variables which may be assumed at choice are (1) the temperature of the entering air t_1; (2) the relative humidity of the entering air h_1; (3) the temperature to which the air is heated before it enters the lumber t_2; and (4) the degree of saturation of the air leaving the lumber, h_3. From these, h_2, t_3, and the volumes and weights of the air and vapor are determined.

Entering air		After heating before entering lumber			Leaving lumber		Weight of 1 c.c. of mixture in grams	
t_1	h_1	t_2	h_2	Dew-point	t_3	h_3	Entering at t_2h_2	Leaving at t_3h_3
Degrees	*Per cent*	*Degrees*	*Per cent*	*Degrees*	*Degrees*	*Per cent*		
32	100	158	2	32	78.8	100	.0010264	.0011658
32	100	158	2	32	110.5	25	.0010264	.0011057
86	100	158	13	86	99.5	100	.0010126	.0011094
86	100	158	13	86	140.5	25	.0010126	.0010394
140	100	158	63	140	140.9	100	.0009525	.0009779
140	100	158	63	140	151.7	75	.0009525	.0010154
86	100	212	4	86	105.8	100	.0009310	.0010915
86	100	212	4	86	146.3	25	.0009310	.0010255
176	100	212	47	176	176.5	100	.0007820	.0008221

that the spontaneous cooling of the mixture produced by the evaporation alone increases its density.

This fact is of great significance, and the method adopted of piling the lumber in the new kiln takes advantage of this principle.

Method Used in Calculating Table IX.—1. The temperature, t_3, of the air leaving the lumber is determined first, as for Table I. The dewpoint must also be determined in order to determine the vapor pressure e.

2. The following equation gives the value of the density (grammes per cubic centimeter) of the mixture of air and vapor:

$$d = \frac{B - 0.378\,e}{760} \times \frac{.00129305}{1 + .003670\,t} \; *$$

B = total barometric pressure in millimeters of mercury.
e = pressure of the vapor in the mixture.
t = temperature Centigrade of the mixture.
.00129305 is the weight in grammes of 1 c.c. of dry air at 0° C., pressure 760 mm. under gravity at 45° latitude and sea level. The figure .003670 is the coëfficient of thermal expansion of air at 760 mm.

The first fractional expression may be explained as follows:

Let d_1 = density of dry air at B-e m.m pressure.
d_v = density of vapor at e m.m. pressure
Then $d = d_1 + d_v$. The air pressure alone is $B-e$

$$\text{and } d_1 = d_0 \frac{B-e}{760}$$

$$d_v = .622 \times d_0 \times \frac{e}{760}$$

where 0.622 is the density of vapor compared to air at 760 pressure.

* See Smithsonian Meteorological Tables, Table 83 to 86.

Whence $d = d_0\left\{\frac{B-e}{760} + \frac{.622\times e}{760}\right\} = d_0\left\{\frac{B-.378e}{760}\right\}$

Knowing the values t_2 and t_3 and the vapor pressures at these two points (pressures at the dewpoints), the values of d_2 and d_3 are obtained from the above equation.

It will be noted that in every case chosen in Table III, the density *increases,* due to evaporation, hence, the tendency of the air is to *descend* as it passes through the pile of lumber.

CHAPTER XI

EFFECT OF DIFFERENT METHODS OF DRYING UPON THE STRENGTH AND THE HYGROSCOPICITY OF WOOD

A RESEARCH was conducted from June, 1905, until October, 1908, at the Forest Service Timber Test Laboratory at Yale University, at that time being conducted in coöperation with the university, to determine the effect of subjecting both green and air dry wood to various temperatures and humidities of the surrounding medium for different lengths of time. Comparative tests were then made in both static bending and static compression on the untreated and treated specimens. The plan followed was to cut the material into carefully selected series of matched specimens. Seven series for each kind of test and each treatment were prepared from fresh green wood and the values of the corresponding sets averaged. This gave an average of seven tests for each individual determination. Each series was composed of six "sets" of specimens, numbered from 1 to 7 for the bending and from 11 to 17 for the compression, coördinate throughout each of the seven series, each set receiving a separate treatment. Sets 1 and 3 were used untreated as standards for comparison for the green and the air

dry, respectively. The treatments of each "set" throughout all of the experiments can best be shown in tabulated form, thus:

Set 1—(standard) soaked green.

Set 2—soaked, subjected to process, resoaked, and compared with Set 1.

Set 3—(standard) air dried about two years.

Set 4—air dried, subjected to process, air dried together with Set 3 about one year after treatment.

Set 5—soaked, subjected to process, air dried about one year together with Sets 3 and 4.

Set 6—soaked, subjected to process, generally tested directly to show the direct effect of the treatment.

The bending tests were made with a span of 26 inches, the specimens being 2 inches high and 1½ inches wide, and the compression specimens were 1½ × 1½ × 5¾ inches, except when cut to smaller size on account of shrinkage. All specimens were treated in the rough and cut to exact size at time of test.

The moisture determinations were made by the usual method of cutting an inch disc across the block at the region of failure and drying in an oven at 98° Centigrade. The loss in weight times 100 divided by the dry weight is the moisture per cent. used. Another check disc was cut from some other portion of the stick in each case and the moisture determined in the same manner.

Three species of wood were used: White ash from Connecticut, loblolly pine from Charleston, S. C., and red oak from Connecticut. More kinds of treatment were given the pine and oak than the ash. Each treatment is designated by the term "process" to avoid confusion with the common use of the word "treatment" as referring to impregnation with creosote. The processes included dry air, moist air, saturated steam, superheated steam, and temperatures from 145° to 331° Fahrenheit. The processes are given in Tables VII, VIII, and IX.

The research embodies over two thousand mechanical tests on carefully selected and matched specimens, and thirty-seven processes, and covered a period of over three years. The full report of the research is filed at the Madison Laboratory of the Forest Service (Project L-16). The high temperature and high pressure treatments were made in a small iron cylinder twelve by forty-four inches in size, which was constructed especially for the purpose. The kiln drying treatments at 145° F. were made in a masonry-lined room heated by horizontal layers of steam pipes, and the higher temperature drying in a water-jacketed copper oven.

In the tables a minus sign indicates a reduction of strength as compared to the respective standards and a plus sign shows an increase.

The results are given in comparative terms to the standards, and the values of the modulus of rupture and the crushing strength only are used in the comparisons for brevity. These tables have been greatly abridged from original report, and are intended to show only the general conclusions. In order to make the comparisons as clear as possible, the values for Sets 4 and 5 have been corrected for moisture so that they correspond to the same moisture condition as the standards, Set 3. For this purpose the moisture strength curves in the files of the Forest Service were used. The curve for black oak has been used as applying to red oak and the compression strength curve has been used in reducing the values for the modulus of rupture. This may account for the apparent increase in strength shown in the air drying compression tests in the red oak table, Processes A to D.

TABLE XI.—WEAKENING EFFECT OF VARIOUS PROCESSES OF DRYING ON THE STRENGTH OF WHITE ASH

Process	Reduction in strength in per cent. of normal					
	Compression sets			Bending sets		
	2 soaked	4 air-dry	5 air-dry	2 soaked	4 air-dry	5 air-dry
A. Dry air 145° F., 25 days	−23.4	0	0	− 9.5	0	+5
G. Saturate steam 212° F., 1 hour	−12.5	0	0	.....	...	...
H. Saturate steam 212° F., 4 hours	−10.3	0	0	− 1.8	0	+2
L. Saturate steam 90 lbs. 331° F., 1 hour	−44.7	−27	0	......	...	...
M. Saturate steam 90 lbs. 331° F., 5 minutes	−24.8	− 4	0	−16.0	−3	0
N. Exhaust steam 145°, 19 days	−15.2	0	0	+ 0.2	0	0
R. Superheated steam 331° F., at atmospheric pressure, 6 hours	−11.9	0	−3	−22.8	...	..

+ Increase in strength.
− Decrease in strength.

Results of Treatments.—Two general effects were noted: (1) That all processes used in this research reduced the strength of the wood, when it was resoaked and compared with the untreated green-soaked standard; and (2) that the hygroscopicity was reduced by most of the treatments and the color darkened, particularly in the higher temperature treatments. This means a reduction in the subsequent shrinkage and swelling or the "working" of the wood, as it is called.

TABLE XII.—WEAKENING EFFECT OF VARIOUS PROCESSES OF DRYING ON THE STRENGTH OF LOBLOLLY PINE

Treatment	Reduction in strength in per cent. of normal—					
	Compression sets			Bending sets		
	2 soaked	4 air-dry	5 air-dry	2 soaked	4 air-dry	5 air-dry
A. Dry air 145° F., 26 days	−21.0	0	*	−15.4	− 2	*
B. Dry air 170° (bending tests), 8 days	....	....		−14.4	− 6	
C. Dry air 200°, 3 days	−13.1	0		−25.3	− 5	
D. Dry air 250°, 6 hours	−20.0	0		.....	...	
Note.—B, C, and D were all dried under A previously.						
F. Saturate steam 212°, 8 hours	−20.0	0		......	....	
G. Saturate steam 212°, 1 hour	−24.8	0		......	....	
H. Saturate steam 212°, 4 hours	−19.7	0		−0.9	0	
K. Saturate steam, 90 lbs., 331° F., 15 minutes	−27.3	− 9		......	....	
L. Saturate steam, 90 lbs., 331° F., 4 hours	−36.6	−42		......	....	
M. Saturate steam, 30 lbs., 274° F., 4 hours	−22.1	−11		−24.3	−10	
N. Exhaust steam 145°, 22 days	−24.5	0		−18.3	0	
P. Exhaust steam 145° F., 22 days, followed by exhaust steam 170° 2 days (previously with N)	−21.7	− 2		......	....	
R. Superheated steam atmos. pressure 274° F., 4 hours	−18.0	+0		− 9.0	0	
S. Superheated steam, 30 lbs. pressure, 298° F., 4 hours	−20.8	− 8		......	....	

* The values for sets 5 have not been carried through the lengthy operation necessary for corrections for moisture and variations from normal, and are therefore omitted from this table. When compared directly with sets 4, however, they appear weaker, with the exceptions of processes A, C, and N in compression and process A in bending. This lesser strength of sets 5, shown especially in the bending tests, may be due to checking of the wet wood (set 5 being soaked before processing) which might weaken the beams more than the compression pieces.

It will be noted that the oak is injured much more than the ash or pine. No significant injury in the subsequently air dried condition in the case of loblolly

TABLE XIII.—WEAKENING EFFECT OF VARIOUS PROCESSES OF DRYING ON THE STRENGTH OF RED OAK

Process	Reduction in strength in per cent. of normal—					
	Compression sets			Bending sets		
	2 soaked	4 air-dry	5 air-dry	2 soaked	4 air-dry	5 air-dry
A. Dry air 145° F., 30 days...... ...	−7.9*	+16.3	... ..	−7.2*	−14.8	......
B. Dry air 170° F., 8 days...	−7.3	+ 5.5	......	− 4.9	−18.7	......
C. Dry air 200° F, 7 days..........	−3.3	+ 3.3	......	− 4.4	− 9.8	......
D. Dry air 273-302°, 4½ hours	−9.5	+ 2.8	......	......	......	......
Note.—B, C, and D were each dried in Process A at first.						
F. Saturate steam 212° F., 8 hours.	− 9.0	−12.5	− 5.7	......	......	......
G. Saturate steam 212° F, 1 hour...	+13.8†	− 4.4	+ 1.1	....	...	......
H. Saturate steam 212° F., 4 hours .	− 1.5	− 2 4	.....	− 3.9	−11.3	− 7.8
K. Saturate steam 90 lbs 331° F, 5 minutes but 1 hour in all heating and cooling...	−44.5	−49.1	−13.7	... ..	......	......
L Saturate steam 90 lbs 331° F., 3½ hours but 4½ hours in all	−30.9	−61.3	−24.9	......	.....	− 6.1
M. Saturate steam 30 lbs. 274° F., 3½ hours..... . ..	−47.0	−47.7	......	−24.8	−33.4	......
N. Exhaust steam 145° F., 21 days	− 8 3	+ 9.5	... ..	− 4.1	−10.8	... ..
P Exhaust steam 170° F., 2 days started with Process N.	−10.7	+ 1.1	......	......	......	......
R. Superheated steam 10 lbs at 274° F., 4 hours......	−49 8	−60.0	... ..	−31.1	−58.7	−18.9
S. Superheated steam 30 lbs. 298°, F. 4 hours......	−36.2	−58.2	......	......	... ..	......

* Corrected for temperature difference o. the wet wood; 10 5 per cent. reduction in strength for each 25° F. increase in temperature. Based on tests given in the original report

†Anomalous result, can not be explained, all factors and tests carefully revised show no discrepancies. This value has also been corrected for temperature.

pine is shown in treatments at temperatures of 212° F. or less in the moist air or steam, or up to 250° in dry air. Thirty pounds steam for four hours, however, shows a decided weakening. In the case of red oak no significant injury is evident in the subsequent air-dry condition in dry air up to 273° or 300° F. for four and

a half hours, but saturate steam at 212° for four hours or longer shows a decided loss in strength. Superheated steam at 274° F. shows very great loss in the case of the oak, both in the subsequently air-dry and in the soaked conditions, less loss in the ash, and no loss in the subsequently air-dry condition in the case of the loblolly pine. A study of the tables will reveal other important comparisons.

It is probable that the toughness of the wood was in many instances reduced when the static strength values showed no appreciable falling off. A number of impact tests made at Purdue University, Lafayette, Ind., on analogous material selected from this same lot, showed that the wood which had been subjected to all of the higher temperature treatments was more brittle than normal wood.

In Table XIV the reduction in hygroscopicity produced by the various processes is shown by the actual reduction of moisture content in the air-dry condition as compared with the air-dry standards. In this table a negative sign shows an increase in moisture content.

Results Applied to Commercial Treatment.—In applying these results to commercial treatments of large blocks of wood, the relative sizes should always be taken into consideration, since in larger sizes the material will not become heated through in the same length of time as with the small specimens used in

Table XIV.—Change in Hygroscopicity Produced by the Various Processes

WHITE ASH

Process	Compression			Bending		
	Moisture per cent.	Reduction in moisture compared to set 3 in per cent. of dry wood		Moisture per cent.	Reduction in moisture compared to set 3 in per cent. of dry wood	
	Set 3	Set 4	Set 5	Set 3	Set 4	Set 5
A	14.9	1.1	0.1	15.0	2.0	−0.2
G	14.5	0.8	0.3	....	...	.....
H	14.0	0.8	0.4	15.2	0.8	0.5
L	15.3	4.8	2.9	....	...	.....
M	15.3	3.1	−1.2	14.3	1.8	−0.4
N	15.8	1.7	1.3	15.4	1.4	0.9
R	15.2	3.8	(1.5)	15.9	6.8	.....

See Table I

LOBLOLLY PINE

Process	Compression Set 3	Compression Set 4	Compression Set 5	Bending Set 3	Bending Set 4	Bending Set 5
A	12.7	0.8	0.9	13.4	1.1	1.2
B	....	.....	.....	14.3	2.1	1.8
C	13.5	1.3	1.5	15.4	1.5	1.5
D	13.9	3.0	1.8	....	...	.....
F	12.4	−0.4	−0.6	....	...	.....
G	13.7	+0.4	−0.6	...	...	.....
H	13.8	0	−0.2	14.0	0.2	−0.2
K	13.2	1.8	0.5	....	...	.....
L	13.7	3.6	3.5	...	..	.....
M	14.3	1.3	1.0	13.3	1.6	1.4
N	13.4	1.3	1.5	14.4	1.8	2.0
P	14.1	1.2	1.2	....	..	.....
R	13.3	1.1	−0.1	14.6	2.1	−0.1
S	15.4	1.7	0.8	...	..	.....

See Table II

RED OAK

Process	Compression Set 3	Compression Set 4	Compression Set 5	Bending Set 3	Bending Set 4	Bending Set 5
A	12.4	4.8	2.8	12.9	2.5	2.7
B	12.4	1.8	1.8	13.3	3.8	3.5
C	12.0	2.6	2.5	14.2	3.2	3.1
D	12.6	3.7	2.7	....	...	.....
F	12.0	1.0	0.2	....	...	.....
G	13.3	0.3	0.3	....	...	.....
H	13.3	0.4	.....	14.4	1.0	0.5
K	13.3	3.2	1.6	....	...	.....
L	12.5	2.8	−0.5	....	..	.....
M	12.9	1.9	1.8	13.6	2.5	1.6
N	13.2	2.0	1.8	15.1	3.9	0.5
P	13.2	2.3	1.4	...	..	.....
R	13.4	0.3	.....	13.7	3.6	1.3
S	13.5	2.3	1.3	....	...	.....

See Table III

Note.—Negative sign signifies an increase in moisture.

this research. The interior of large blocks, such as railway ties, will also generally contain considerable moisture, even if treated in dry air or hot oil, which will change the conditions. The result on a large block will vary from the surface to the center, and the condition as a whole will be a combination of the effects produced on the several layers from the surface to the center. Nevertheless, these results will be true of each portion of the wood which becomes subjected to the same condition as those given in this research.

CHAPTER XII

Instruments Useful in Dry Kiln Work and Methods of Testing Wood

(1) *Temperature.*—The determination of the true temperatures in different portions of the dry kiln is of the utmost importance. It is, however, a difficult matter to do. An accurate thermometer does not necessarily register the temperature correctly. It depends upon how it is placed. In fact, it is less important to have the thermometer exact than it is to know how to place it so as to register the temperature which it is desired to determine. It is not uncommon to find standard thermometers reading anywhere from 30° to even 60° in error due to their misplacement. In one kiln which the writer examined a mercurial thermometer was placed in a recess in the front door in such a way that it could be read through a glass from the outside. The air in this kiln was supposed to be entering the lumber at 160° F., and indeed the thermometer so indicated. Upon entering the kiln and hanging a test thermometer near the pile of lumber, where it was allowed to remain for fifteen minutes to come to equilibrium, I was surprised to find the actual temperature to be 230° F.! The thermometer by which the kiln was

operated was in a sheltered nook where it received cold radiation from the door and was indicating seventy degrees too low!

A thermometer should be so located that it can not receive direct radiation either of heat from the steam pipes nor of cold from the lumber or from the door or even the roof or walls of the kiln. Moreover, it must not be placed in stagnant air. Too much importance can hardly be put on the question of the proper placing of the thermometers. Merely to stick a standard thermometer somewhere in the kiln and expect it to give you the correct temperature is as unreasonable as to expect an alarm clock to wake one up at the proper time, without setting it. It matters little what kind of a thermometer is used. An ordinary 50-cent thermometer may be as useful as a $10 standard *if it is properly used.* It is always wise, furthermore, to have more than one thermometer, and to check the two readings, one against the other.

A recording thermometer, with a long, flexible tube connection with the bulb is one of the most useful kinds for a dry kiln, as a weekly record may then be kept continuously. Such instruments can be obtained from any reliable instrument maker and cost from $35 to $65. Mercury-filled connecting tubes have not proved satisfactory for dry kiln use, and the gas-filled kind is strongly advised.

(2) *Humidity.*—The humidity is more difficult to determine than temperature, but does not require complicated instruments. The most satisfactory for the purpose consists of the "Wet-and-dry-bulb Hygrometer," which consists simply of two glass stemmed thermometers hung side by side, the bulb of one being surrounded by a wick which dips into a vessel of water. Such instruments can be procured in the market or can be readily homemade. The essential points are that the wick shall be kept clean, free from grease or scale incrustation; the wick must be thoroughly moist; distilled water should be used in the reservoir and the bulb should be hung where it receives a good draught of air. Otherwise the same precautions which were given for temperature determinations apply to this instrument. The wet-and-dry-bulb readings are taken simultaneously and the humidity may then be quickly determined from the humidity chart given in Chapter XIV. As it is fully explained, further remarks are unnecessary here. The wet-and-dry-bulb hygrometer is sometimes known as a "hygrodeik."

A form of this instrument adapted to the recording thermometer is now being manufactured by the makers of the recording thermometers, with the two pens recording on the same dial. A caution in the use of this recording hygrometer is necessary, first, that the wicks and reservoir must be so arranged as to insure

that the bulb be kept continually wet, and, second, that the wet bulb be placed so that it will receive a full current of air.

A hand instrument inclosed in a convenient case having a small self-contained electric fan to produce the current of air over the wet bulb is on the market, and is a useful form of this hygrometer.

There are a number of direct reading *hygrometers.* Of these the small dial instruments which operate by a fine spiral band composed of two thin layers, one of metal and the other of some hygroscopic material, have proved too perishable for dry kiln work and are not recommended for this purpose. Another form of hygrometer in which the hand on a dial is operated by a number of fine hairs is more satisfactory, but rather too perishable for steady work.

Disks of paper or cloth soaked in a solution of cobalt chloride are a very good rough indicator as to whether the air is very damp or dry. When dry the cobalt chloride turns a brilliant blue, when damp it is pink, the changing point being in the neighborhood of 60 per cent. humidity.

(3) *Determination of Moisture in the Wood.*—Different wood users have various empirical methods of deciding whether wood is sufficiently dry for their use. Many of these are based on long and intimate personal experience in the qualities of the wood as affected by

the moisture, and a discussion of them here would not be of much service, since such knowledge can be gained only by observation and experience. There is, however, a simple and accurate method which anyone can make use of. It consists in taking a suitable sample of the wood to be tested, weighing it, then drying it either in an oven heated to about 212° or simply laying it on top of a radiator until it ceases to lose weight, then weighing again. The loss in weight is the amount of moisture which the piece contained, and this loss divided by the dry weight times 100 is the *moisture per cent.* as scientifically used, the dry weight of the wood being the basis of the percentage expression. Sometimes the wet weight has been used in expressing the moisture per cent., but this is not a good value to use, since it is a very variable quantity, whereas the dry weight of the specimen is a constant. In obtaining the sample, the method is to cut a disc about one inch thick in the direction of the grain, clear across the center of a representative board or stick. A disc from the end of the board will not answer the purpose, as the end is apt to have dried out considerably more than the rest of the board.

For the weighing of these moisture discs a small balance, such as is used in apothecaries' shops, is suitable, with weights from 1000 grammes to one gramme,

or 500 grammes to one centigramme, according to whether large or small work is to be conducted. If pounds are used it is convenient to have the graduations in hundredths rather than in ounces and grains.

If estimates have been given in per cents of the green weights, the values may be converted into the standard moisture per cents by dividing by 100-G, thus

$$P = \frac{G}{100-G} \times 100$$

where G is the moisture per cent. of the green weight and P that of the dry.

The moisture distribution is often important to know, and this may be determined by cutting an extra disc and subdividing this transversely into an inner and outer portion.

For some purposes the degree of dryness desired may be approximately determined by shrinkage measurements. A sample is removed from the kiln and its width measured. This is then dried in an oven or over steam pipes and again measured. If the shrinkage is more than a specified amount, the material is not sufficiently dry. Taking the correct condition to be 5 per cent. of moisture, the permissible shrinkage by this method per inch width of plain sawed boards for a number of species is as follows:

TABLE XV.

Species	Plain	Quartered
	Inch	Inch
Ash, white	.011 to .015	.007 to .009
Basswood	.014 to .017	.010 to .011
Beech	.017 to .018	.008 to .009
Birch, yellow	.015	.012 to .013
Cherry, black	.012	.006
Chestnut	.011	.006
Cypress	.010	.006
Fir, Douglas	.013	.008
Gum, black	.013	.007
Gum, red	.017	.009
Locust, black	.011	.007
Mahogany, Cuban	.0055	.0045
Mahogany, African	.009	.008
Maple, hard	.015	.008
Oak, white (alba)	.014 to .015	.008 to .010
Oak, red (rubra)	.014	.006 to .007
Oak, post	.018	.010
Oak, swamp white	.018	.009
Pine, longleaf	.012	.009
Pine, sugar	.009	.005
Pine, western white	.012	.007
Pine, western yellow	.011	.007
Pine, eastern white	.010	.004
Walnut, black	.012	.009

Permanent Casehardening.—This condition is readily determined by cutting a narrow disc across the board and then slotting it crosswise into a number of prongs as shown in Fig. 24-A, page 120. If the prongs do not at first bind on the saw, but subsequently begin to close up after drying or in a warmed room, it indicates that the stick was not uniformly dry, but contained more moisture in the center than on the surface.

CHAPTER XIII

Temperatures and Humidities for Drying Various Kinds of Lumber

As explained fully in Chapter V, any statement in general of suitable temperatures and humidities without qualification as to where they apply and the method of drying is not only misleading but meaningless. For drying a single stick of wood it would be feasible to prescribe not only the best temperatures and humidities, but also the length of time required, starting at any given moisture content, but with a pile of lumber this is obviously impossible. It might at first thought be supposed that, assuming a direct circulation through a pile of specified size, the conditions for the *entering air* should be the same as for a single stick by itself. Even this, however, may not always be strictly the case, for the reason that in order to secure a reasonable rate of drying for the rest of the pile it is often desirable to *slightly exceed* the best conditions for a single stick in respect to the temperature and dryness of the entering air. This is done at some risk to lumber on the entering side of the pile, but may be necessary in some cases for practical operation. In this connection it must be borne in mind that it is not possible to dry an entire pile of lumber as perfectly as a few pieces can be dried. Some sacrifice in quality,

or in time must be made to quantity in commercial operations.

The clearest way in which to show the drying conditions is by means of curves on cross-section paper, in which time in days is the horizontal distance, or abscissa, and the temperature, the relative humidity, and the moisture content of the wood expressed in per cent. of the dry weight, as the vertical distances or ordinates. These temperatures, humidities, and percentages may be all expressed by a single set of figures on the vertical axis running from 0 to 180 or higher, as the case may be, and interpreted as Degrees Fahrenheit, Per Cents of Relative Humidity, or Moisture Per Cents, according to the respective curves in question.

The following diagrams express what have been found by experiment to give the best drying results for a number of species of wood. They must be interpreted as applicable to a pile of lumber (slant pile, for example, as shown in Fig. 44, page 192, in which the air enters the pile at one side, passes rapidly through the layers and leaves at the opposite side). The width of the pile, unless otherwise stated, is taken as only four or five feet. The main curves, heavy lines, give the suitable temperatures and humidities of the *air just entering the pile* at the different stages of the drying process. Curves marked T are for temperature, H, relative humidity, and D, dewpoint. The conditions of the *air leaving* the pile can not be stated, but will

vary with velocity of circulation and width of pile. The two dash curves are the approximate moisture per cents, the lower one being for boards on the entering side of the piles and the upper one for the leaving side. The horizontal distance between *the two is the lag* in drying, due to the size of the pile. The time of drying indicated by the lower curve is, *therefore, the minimum.* The actual time required will be in excess of this, according to the width of the pile and the velocity of the air movement. The upper dash curve (when shown) is for the *leaving* side of a slant pile four feet in width when the air velocity is sufficient to carry it through the pile in two to three seconds.

The curves apply to rough boards one inch in thickness with stickers of the same thickness. For drying other thicknesses of lumber the time ordinate should be increased in proportion to the thickness up to three inches and about one and a half times the thickness for thicknesses over three inches. In other respects the curves should be unchanged. *For one-half inch or less* the time should be decreased as the square of the fractional part of an inch. Thus for one-half inch in thickness the time should be one-quarter of that indicated in the curves. Planed lumber will dry considerably faster than rough. Quarter-sawed lumber will generally require 25 to 50 per cent. longer to dry than plain sawed.

The curves are inclusive of all conditions from green

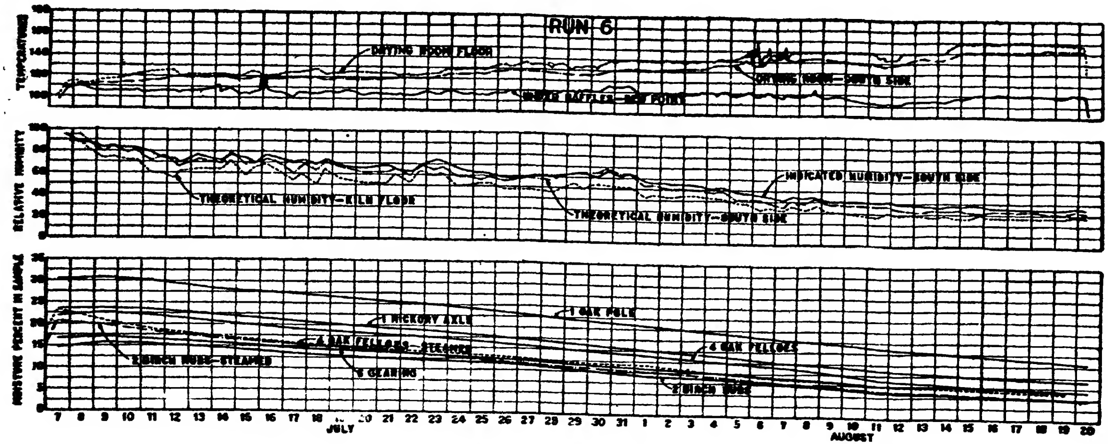


Fig. 53.—Curves for an actual drying run on oak, hickory, and birch wagon stock.

to dry. In starting with partially dry lumber, look for the corresponding moisture per cent. on the lower Moisture Per Cent. Curve, and begin with conditions as indicated for this point. Thus, for thoroughly air-dried red gum (see Plate No. 1) containing 15 per cent. moisture, start with the conditions as given for the tenth day, 130° and 61 per cent. humidity, and follow the curve from then on as before. It is always well, however, to give the air-dried lumber a preliminary treatment of one or two days in saturated air until the pile is heated clear through to the required temperature. Steaming at a slightly higher temperature for the first 12 hours to one day is effective in heating the lumber and removing temporary casehardening by moistening the surface.

The Drying Curves given in Plates I to VII are not to be interpreted as hard-and-fast rules, but must be used with intelligence and understanding. The length of time of drying (ordinates), especially, will vary according to circumstances and the initial moisture content of the wood. Take, for example, Plate I, primarily for one-inch green red gum. The moisture per cent. curves start with 110 per cent. for the green wood. If the lumber to be dried averages less than this, say 60 per cent., the time of drying may be somewhat shortened. In fact, the conditions may be started with those indicated for the third day. A great deal depends also upon the use to which the wood is to be put. Thus

yellow birch can be most satisfactorily dried for high-grade furniture by the conditions indicated in Plate I, but this may be too slow in many cases, and then Plate III may be followed, but the lumber will not be as free from internal stresses as when dried by the slower method. Again, maple may be dried by Plate I with the least amount of damage, but when the white color of the sapwood is of prime consideration it must be dried at a lower humidity as given in Plate II.

Species for which a high temperature is indicated can almost always be dried to even better conditions by a lower temperature method and a longer time, but the reverse is not true. The idea of the curves is to indicate not a slow method of drying, but rather the upper limit—the maximum conditions for producing the most rapid drying without undue injury to the material.

Furthermore, it is generally true that the thinner the material the more intensive may the drying conditions be made. For example, while one-inch black walnut can be successfully dried by Plate I, for two and a half to three-inch thickness a lower temperature is desired as given in Plate IV. Or, again, one-inch maple may be dried as shown in Plate II, but for maple last blocks, the conditions given in Plate IV are recommended.

With the foregoing explanations the curves, Plates I to VII, are recommended for the species indicated in Table XVI:

TABLE XVI.—LIST OF SPECIES FOR DRYING CURVES

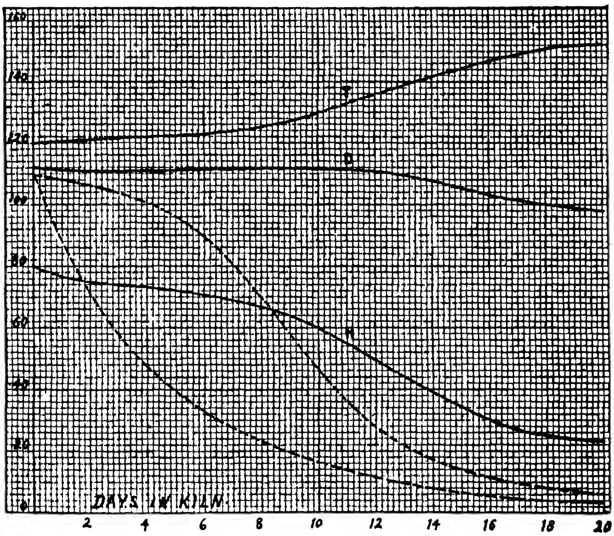
Plate of curves	Principal species	Probable species *	Remarks
I 1 inch thick	Red gum Black gum Black walnut[1]	Holly Cherry Cucumber Mahogany[2] Beech Sycamore Hard maple	Suitable for most medium, dense hardwoods, but time of drying will vary with species. Spruce for special uses.
II 1 inch thick	Select sap hard maple Select Basswood	Select white birch Yellow birch Butternut Ash[2]	The low humidity in this run is required to prevent the white maple sap wood from turning pink. A low temperature below the fiber saturation point is to prevent undue shrinkage of the heartwood.
III 1 inch thick	Yellow birch Ash[2] Chestnut	Poplar Cottonwood Willow Tulip Elm Hackberry Butternut	Suitable for many of the light hardwoods. Time of drying will vary according to hardness of the wood and moisture content.
IV 2½ inches thick; also shaped thick blanks	Black walnut Hard maple shoe lasts Round dogwood Round ironwood Mahogany Oak(2 ″thick)	Also 1 to 2-inch Persimmon Lignum vitæ and very hard woods Eucalyptus Hickory, locust Osage orange	Suitable for irregular heavy blanks. By prolonging the time almost any wood can be successfully dried by this process.
V 1 inch thick	Western larch	Cypress	For species weak in tension across the grain.
VI 1 inch thick	Western red cedar Redwood	Select white pine Sugar pine Western yellow pine	Especially "sinker" stock or butt logs which often collapse in drying.
VII 1 inch thick	Hemlock Douglas fir Southern yellow pines Tamarack Incense cedar	Spruces[2] Sap white pine Cedars Sugar Pine Western yellow pine	Some of these species may also be dried in *superheated steam*, but not so eastern hemlock. Sugar Pine apt to brown stain.

* This column is included provisionally, with the understanding that it may not be strictly applicable.

[1] Where strength is of prime importance as for aeroplanes, dry mahogany and Black Walnut by conditions indicated by Plate IV.

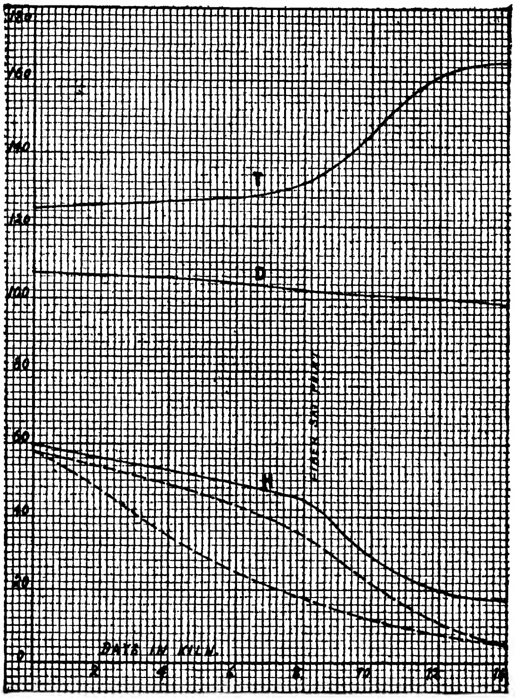
[2] For special purposes where strength is vital dry by Plate I.

PLATE I



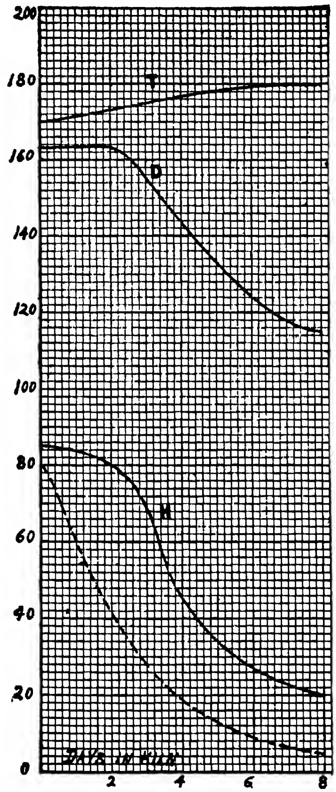
Drying Conditions Suitable for One Inch Red Gum, Black Gum and Black Walnut

PLATE II



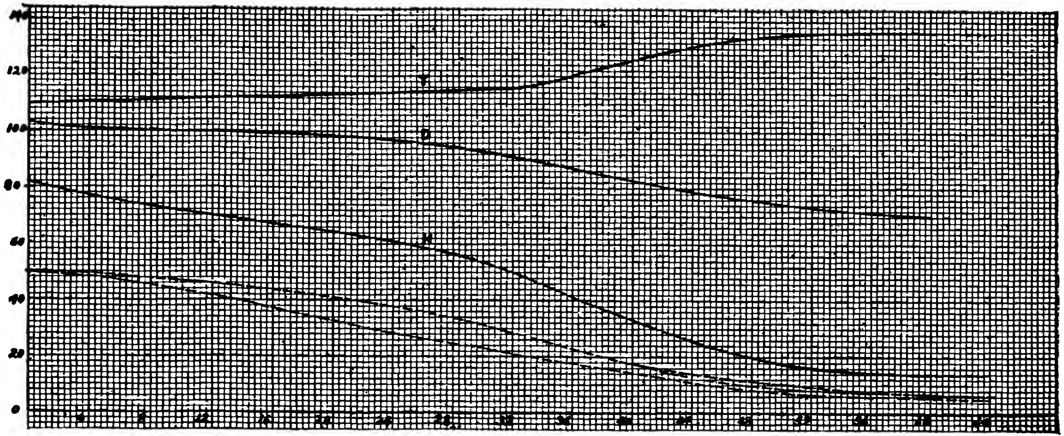
Drying Conditions Suitable for One Inch Select Sap Hard Maple and Select Basswood.

PLATE III



Drying Conditions Suitable for One Inch Yellow-Birch, Ash and Chestnut, for Ordinary Purposes.

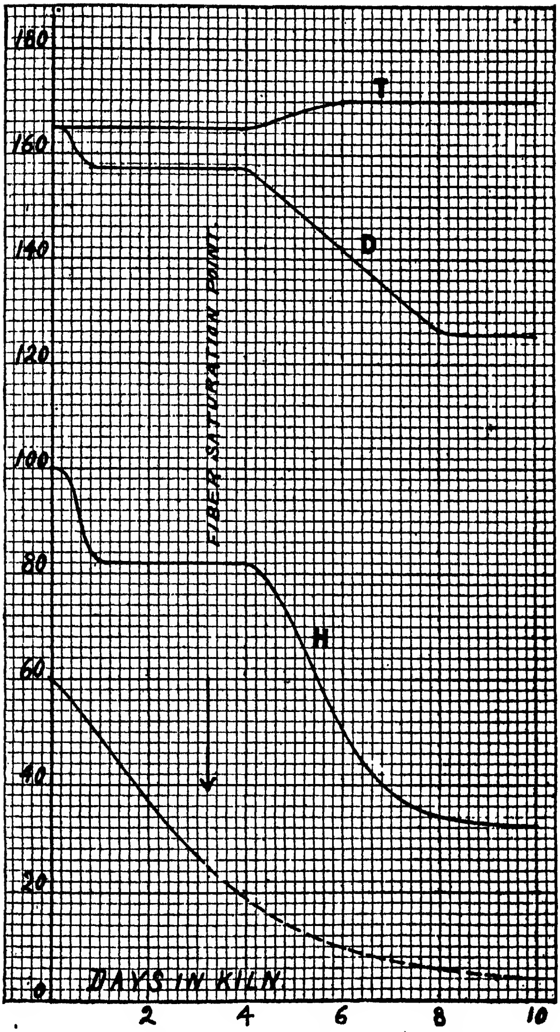
PLATE IV



Days in Kiln

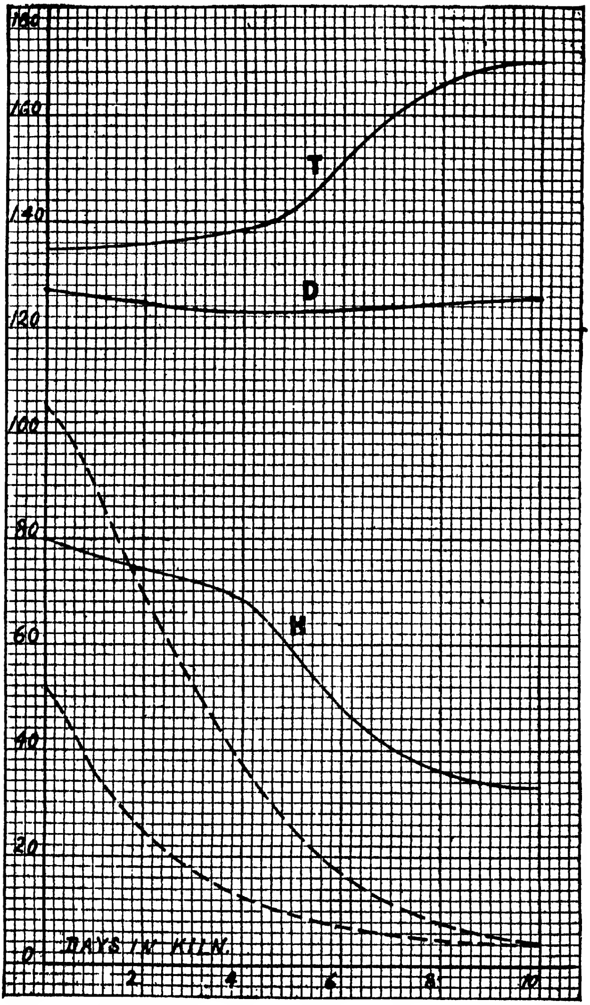
Drying Conditions Suitable for Black Walnut, Red and White Oaks, and other dense hardwoods not over 2½ Inches Thick. Also for Mahogany and Black Walnut one-inch boards for special uses, the time of drying being reduced ⅔ for the one-inch thickness.

PLATE V



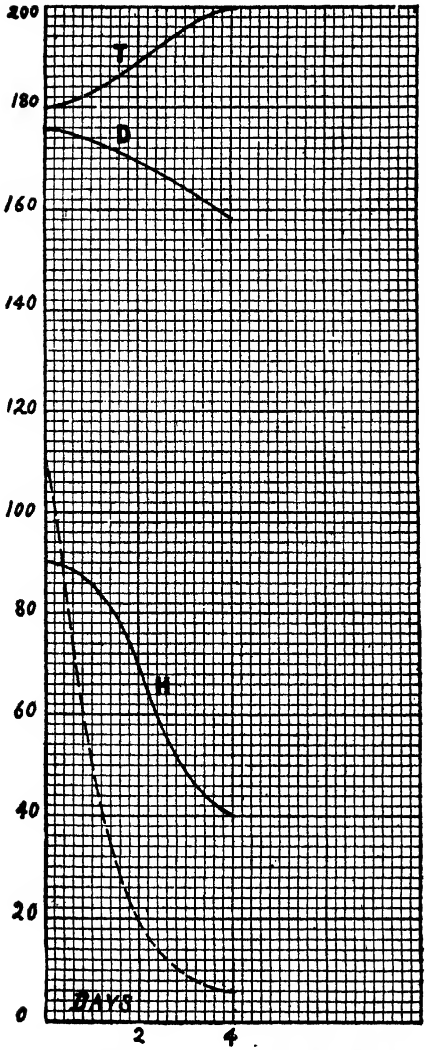
Drying Conditions Suitable for One Inch Western Larch and Cypress.

PLATE VI



Drying Conditions Suitable for Western Red Cedar, and Redwood "Sinker" Stock, One Inch Thick.

PLATE VII



Drying Conditions Suitable for Douglas Fir, Yellow Pines, Incense Cedar and Many Other Softwoods.

CHAPTER XIV

Humidity Diagram [1]

PURPOSE AND CONSTRUCTION

The purpose of the humidity diagram is to enable the dry-kiln operator to determine quickly the humidity conditions and vapor pressures, as well as the changes which take place with changes of temperature. The diagram (Plate VIII) is adapted to the direct solution of problems of this character without recourse to tables or mathematical calculations.

The humidity diagram consists of two distinct sets of curves on the same sheet. One set, the convex curves, is for the determination of relative humidity of wet-and-dry-bulb hygrometer or psychrometer; [2] the other, the concave curves, are derived from the vapor pressures and show the amount of moisture per cubic foot at different relative humidities and temperatures when read at the dewpoint. The latter curves, therefore, are independent of all variables affecting the wet-bulb readings. The short dashes show the correction (increase

[1] From Forest Service Bulletin 104, by the author, 1912.

[2] For a full explanation of the psychrometer, see Weather Bureau Bulletin No. 235, "Psychrometer Tables," and also "Smithsonian Meteorological Tables."

Fig. 54.—Humidity regulated experimental kilns at the Forest Products Laboratory.

or decrease) which is necessary in the relative humidity, read from the convex curves, with an increase or decrease from the normal barometric pressure of 30 inches, for which the curves have been plotted. This correction, except for very low temperatures, is so small that it may usually be disregarded.

The ordinates, or vertical distances, are relative humidity expressed in per cent. of saturation, from 0 per cent. at the bottom to 100 per cent. at the top. The abscissæ, or horizontal distances, are temperatures in degrees Fahrenheit from 30° below zero at the left to 220° above at the right.

EXAMPLES OF USE

The application of the humidity diagram can best be understood by sample problems. These problems also show the wide range of conditions to which the diagram will apply.

(1) *To find the relative humidity by use of wet-and-dry-bulb hygrometer or psychrometer.*

Place the instrument in a strong circulation of air, or wave it to and fro. Read the temperature of the dry bulb and of the wet, and subtract. Find on the horizontal line the temperature shown by the dry-bulb thermometer. Follow the vertical line from this point till it intersects with the convex curve marked with the difference between the wet and dry readings. The

horizontal line passing through this intersection will give the relative humidity.

Example: Dry bulb 70°, wet 62°, difference 8°. Find 70° on the horizontal line of temperature. Follow up the vertical line from 70° till it intersects with the convex curve marked 8°. The horizontal line passing through this intersection shows the relative humidity to be 64 per cent.

(2) *To find how much water per cubic foot is contained in the air.*

Find the relative humidity as in example No. 1. Then the nearest concave curve gives the weight of water in grains per cubic foot when the air is cooled to the dewpoint. Using the same quantities as in example No. 1, this will be slightly more than 5 grains.

(3) *To find the amount of water required to saturate air at a given temperature.*

Find on the top line (100 per cent. humidity) the given temperature; the concave curve intersecting at or near this point gives the number of grains per cubic foot. (Interpolate, if great accuracy is desired.)

(4) *To find the dewpoint.*

Obtain the relative humidity as in example No. 1. Then follow up parallel to the nearest concave curve until the top horizontal line (indicating 100 per cent. relative humidity) is reached. The temperature on this horizontal line at the point reached will be the dewpoint.

Example: Dry bulb 70°, wet bulb 62°. On the vertical line for 70° find the intersection with the hygrometer (convex) curve for 8°. This will be found at nearly 64 per cent. relative humidity. Then

follow up parallel with the vapor pressure (concave) curve marked 5 grains to its intersection at the top of the chart with the 100 per cent. humidity line. This gives the dewpoint as 57°.

(5) *To find the change in the relative humidity produced by a change in temperature.*

Example: The air at 70° F. is found to contain 64 per cent. humidity; what will be its relative humidity if heated to 150° F.? Starting from the intersection of the designated humidity and temperature coördinates, follow the vapor pressure curve (concave), until it intersects the 150° temperature ordinate. The horizontal line then reads 6 per cent. relative humidity. The same operation applies to reductions in temperature. In the above example what is the humidity at 60°? Following parallel to the same curve in the opposite direction until it intersects the 60° ordinate gives 90 per cent.; at 57° it becomes 100 per cent., reaching the dewpoint.

(6) *To find the amount of condensation produced by lowering the temperature.*

Example: At 150° the wet bulb reads 132°. How much water would be condensed if the temperature were lowered to 70°? The intersection of the hygrometer curve for 18° (150°–132°) with temperature line for 150° shows a relative humidity of 60 per cent. The vapor-pressure curve (concave), followed up to the 100 per cent. relative humidity line, shows 45 grains per cubic foot at the dewpoint, which corresponds to a temperature of 130°. At 70° it is seen that the air can contain but 8 grains per cubic foot (saturation). Consequently there will be condensed 45 minus 8 or 37 grains per cubic foot of space measured at the dewpoint.

(7) *To find the amount of water required to produce saturation by a given rise in temperature.*

Example: Take the values given in example No. 5. The air at the dewpoint contains slightly over 5 grains per cubic foot. At 150° it is capable of containing 73 grains per cubic foot. Consequently 73 minus 5 equals 68 grains of water which can be evaporated per cubic foot of space at the dewpoint when the temperature is raised to 150°. But the latent heat necessary to produce evaporation must be supplied in addition to the heat required to raise the air to 150°.

(8) *To find the amount of water evaporated during a given change of temperature and humidity.*

Example: At 70° suppose the humidity is found to be 64 per cent. and at 150° it is found to be 60 per cent., how much water has been evaporated per cubic foot of space? At 70° temperature and 64 per cent. humidity there are 5 grains of water present per cubic foot at the dewpoint (example No. 2). At 150° and 60 per cent. humidity there are 45 grains present. Therefore 45 minus 5 equals 40 grains of water which have been evaporated per cubic foot of space, figuring all volumes at the dewpoint.

(9) *To correct readings of the hygrometer for changes in barometric pressure.*

A change of pressure affects the reading of the wet bulb. The chart applies at a barometric pressure of 30 inches, and, except for great accuracy, no correction is generally necessary.

Find the relative humidity as usual. Then look for the nearest barometer line (indicated by dashes). At the end of each barometer line will be found a fraction which represents the proportion of the relative humidity already found, which must be added or subtracted for a change in barometric pressure. If the barometer reading is less than 30 inches, add; if greater than 30 inches, subtract. The figures given are for a change of 1 inch; for other changes use proportional amounts. Thus for a change of 2 inches use twice the indicated ratio, for half an inch use half, and so on.

Example: Dry bulb 67°, wet bulb 51°, barometer 28 inches. The relative humidity is found, by the method given in example No. 1, to equal 30 per cent. The barometric line (dashes) gives a value of $\frac{3}{100}H$

for each inch of change. Since the barometer is 2 inches below 30, multiply $\frac{3}{100}$ *H* by 2, giving $\frac{6}{100}$ *H*. The correction will therefore be $\frac{6}{100}$ of 30, which equals 1.8. Since the barometer is below 30, this is to be added, giving a corrected relative humidity of 31.8 per cent.

This has nothing to do with the vapor pressure (concave) curves, which are independent of barometric pressure, and consequently does not affect the solution of the previous problems.

(10) *At what temperature must the condenser be maintained to produce a given humidity?*

Example: Suppose the temperature in the drying room is to be kept at 150° F., and a humidity of 80 per cent. is desired. If the humidity is in excess of 80 per cent. the air must be cooled to the dewpoint corresponding to this condition (see problem No. 4), which in this case is 141.5°.

Hence if the condenser cools the air to this dewpoint, the required condition is obtained when the air is again heated to the initial temperature.

(11) *Determination of relative humidity by the dewpoint.*

The quantity of moisture present and relative humidity for any given temperature may be determined directly and accurately by finding the dewpoint and applying the concave (vapor pressure) curves. This does away with the necessity for the empirical convex curves and wet and dry bulb readings. To find the dewpoint some form of apparatus, consisting essentially of

a thin glass vessel containing a thermometer and a volatile liquid, such as ether, may be used. The vessel is gradually cooled, through the evaporation of the liquid, accelerated by forcing air through a tube, until a haze or dimness, due to condensation from the surrounding air, first appears upon the bright outer surface of the glass. The temperature at which the haze first appears is the dewpoint. Several trials should be made for this temperature determination, using the average temperature at which the haze appears and disappears.

To determine the relative humidity of the surrounding air by means of the dewpoint thus determined, find the concave curve intersecting the top horizontal (100 per cent. relative humidity) line nearest the dewpoint temperature. Follow parallel with this curve till it intersects the vertical line representing the temperature of the surrounding air. The horizontal line passing through this intersection will give the relative humidity.

Example: Temperature of surrounding air is 80°; dewpoint is 61°; relative humidity is 53 per cent.

The dewpoint determination is, however, not as convenient to make as the wet-and-dry-bulb hygrometer readings. Therefore, the hygrometer (convex) curves are ordinarily more useful in determining relative humidities.

THEORY OF HUMIDITY DIAGRAM

Relative Humidity Curves.—The relative humidity or convex curves are empirical, depending upon experimental data furnished by the United States Weather Bureau. The curves are based on Ferrel's formula:[3]

$$f = f_1 - 0.000367\, P\, (t - t_1)\left(1 + \frac{t_1 - 32}{1571}\right)$$

in which

t = temperature of the dry bulb in degrees Fahrenheit.

t_1 = temperature of the wet bulb in degrees Fahrenheit.

f = actual vapor pressure in the air in inches of mercury.

f_1 = maximum vapor pressure at the temperature of wet bulb t_1.

P = barometric pressure in inches of mercury.

If F be the maximum vapor pressure at the dry-bulb temperature t, then the relative humidity is $\frac{f}{F}$.

The constants for Ferrel's equation were obtained by a great number of careful experiments conducted by Professors Marvin and Hazen, of the United States Weather Bureau. The equation applies correctly only when the psychrometer is subjected to a strong current of air having a velocity of at least 15 feet per second.

[3] For this formula and for much of the tabulated data upon which the curves are based, the author is indebted to the publications of the Weather Bureau and Smithsonian Institution referred to in the second footnote on p. 286.

It is strictly applicable only below 140° F., since the constants of the equation have been deduced from experiments conducted only at temperatures below this. Experiments made by the author indicate, however, that the equation holds with reasonable exactness for temperature up to the boiling point, and the curves have therefore been extended to 220°.

The curves as plotted are for a barometric pressure of 30 inches, and since P enters into the equation a correction must be made for exactness at other pressures. This correction is shown by the intersecting dashes as a proportion of the indicated humidity, so that it may be made direct from the curves with little extra calculation. These correction lines were derived in the following manner:

Let P and H be the variables and t, t_1, f_1, and F constant. Let C be a constant factor. Since $H = \frac{f}{F}$

$$H = \frac{f_1 - CP}{F} \qquad H_1 = \frac{f_1 - CP_1}{F} \tag{1}$$

Then,

$$\frac{H_1 - H}{H} = \left(\frac{f_1 - CP_1}{F} - \frac{f_1 - CP}{F}\right) \times \frac{F}{f_1 - CP} = \frac{C(P - P_1)}{f_1 - CP} \tag{2}$$

That is, other things being constant, the ratio $\frac{H_1 - H}{H}$ is directly proportional to the difference in pressures (P–P_1). Let P–$P_1 = 1$, then

$$\frac{H_1 - H}{H} = \frac{C}{f_1 - CP}$$

Now assume a value for $\frac{H_1 - H}{H}$, say $\frac{1}{100}$, then

$$\frac{C}{f_1 - CP} = \frac{1}{100}, f_1 = 100\,C + CP.$$

But P was taken as 30 in the given curves, therefore

$$f_1 = \frac{130}{30} CP, = \frac{13}{3} CP \tag{3}$$

So also for $\frac{H_1 - H}{H} = \frac{2}{100}, f_1 = \frac{16}{6} CP$, etc.

Now, with these values for f_1 corresponding to $\frac{1}{100}$, $\frac{2}{200}$, etc., proportional differences in the values of H for a 30-inch barometer reading, the values of CP may be calculated for various differences $(t - t_1)$ and the values of f_1 found from this equation (3). The temperature t_1 is thus determined corresponding to f_1 and therefore also the temperature t.

Hence, points may be marked on the curves corresponding to a difference in barometric pressure of 1 inch and a proportional value of H added to or subtracted from the value derived straight from the curves. This proportion is given at the left-hand end of these barometric lines. It will be seen from equation (2) that this amount must be added to H for barometer readings less than 30 inches, and subtracted for readings above 30 inches. The amount is also seen to be directly proportional to the difference in pressure, so that for a fall of barometer of 2 inches twice the indicated amount must be added.

Except for very low temperatures this correction is so small that it may usually be disregarded.

Vapor-pressure Curves.[4]—The vapor-pressure or concave curves indicate the relative humidity or proportional saturation of the air which definite amounts of moisture, read at the dewpoint, will produce at given temperatures. The amounts of moisture are given on the curves in grains per cubic foot of air (or space) at the dewpoint or saturation. The exact weight of moisture present is not given, except at the dewpoint as just stated.

The curves might have been drawn to show the exact weight of moisture present at any given temperature and relative humidity, but by so doing their chief function, the ability to indicate the concurrent variation of the moisture condition with change of temperature, would have been lost. If the barometric pressure remains constant while the temperature changes, the vapor pressure also remains constant; but not so the weight of moisture per cubic foot. The relative humidity is the ratio of the actual vapor pressure to the maximum vapor pressure; hence by drawing these curves to represent vapor pressures instead of weights of vapor, they may be followed strictly from one temperature to another for determining the change which will occur in the relative humidity. The difference between the

[4] Not to be confused with saturate vapor-pressure curves.

density (weight) curves and the vapor-pressure curves is comparatively small, however, within the range of temperature given, and the curves may be read in terms of grains per cubic foot at any point without great error. For example, take a cubic foot of saturated air at 70° F. and heat it to 100°. The concave curves of the humidity diagram show that it originally contained 8 grains of moisture; the saturated vapor-pressure curve shows that the saturate vapor pressure was 0.73 inch of mercury. In heating to 100°, the total pressure of air plus moisture remains unchanged, and therefore the vapor pressure is still 0.73 inch. The vapor, however, has been expanded by the heat so that it now occupies

$$\frac{t_0+100}{t_0+70}=\frac{561}{531}=1.056 \text{ cubic feet,}$$

t_0 being the absolute temperature Fahrenheit. One cubic foot therefore contains $\frac{8}{1.056}=7.57$ grains. The relative humidity by the curves is seen to be 38 per cent. $\left(=\frac{0.73}{1.92}\right)$. Had this air been heated to 170°, 1 cubic foot would contain 6.73 grains instead of 8, and its relative humidity would be $\frac{0.73}{12.2}=6$ per cent., which is shown on the curve. The denominators are pressures of saturated vapor (in inches of mercury) at the respective temperatures.

Saturate Vapor-pressure Curves.—The four curves

saturated vapor, the vertical lines (ordinates) being pressures in inches of mercury, and the horizontal lines (abscissæ) being temperatures. They are in reality one curve drawn in four parts, in as many different scales, each of which is the previous scale magnified by ten. For example, the units on the first part of the curve (on the extreme right) are inches; when the curvature decreases so that this scale can not be read accurately, the curve is broken and the second part is drawn in units of 0.1 inch. Similarly the units shown on the third and fourth parts are, respectively, 0.01 and 0.001 inch.

MEASURES AND WEIGHTS

The following equivalents are given for convenience in making computations:

9° F. = 9° C.
1 inch = 25.4 mm.
1 meter = 39.37 inches.
1 grain = 0.06480 gram.
1 gram = 15.4324 grains.
1 grain per cubic foot = 0.0022883 gram per liter.
1 gram per liter = 436.99 grains per cubic foot.
7000 grains = 1 pound av. = 453.59 grams.
1 U. S. gallon water at 62° F. weighs 8.3360 lbs. av.
1 cu. ft. water at 62° F. weighs 62.36 lbs. av.; at 39° F. (maximum density), 62.43.
1 cu. ft. = 7.48 U. S. gallons.
1 U. S. gallon = 231 cubic inches = 0.1368 cu. ft.
1 imperial gallon water at 62° F. weighs 10 lbs. av. = 277.11 cubic inches.
1 cu. ft. = 6.236 imperial gallons.
1 U. S. gallon = 3.785 liters.
1 imperial gallon = 4.541 liters.

1 cu. ft. = 28.317 liters.
1 cu. ft. of dry air at 32° F. weighs .08071 lb.
1 cu. meter of dry air at 0° C. weighs 1.293 kg.

Coefficient of expansion of air $= \frac{1}{461}$ of volume at 32° F. per degree F.

Ratio weight saturated vapor to weight dry air at same pressure and temperature is nearly constant = 0.6225.

$VP = RT$, where V = volume of gas in cubic feet.
P = absolute pressure in lbs. per cubic foot.
T = absolute temperature $= t + 461$ where t is temperature Fahrenheit.
$R = 53.37$ for air.

Specific heat of air at constant pressure $K_p = 0.2375$ B. t. u. per lb.
$K_p - K_v = (R \div 778)$ where K_v is specific heat at constant volume = 0.1689.

Latent heat of ice........................	= 142	B.t.u. per lb.
Specific heat of ice......................	= 0.504	B.t.u. per lb.
Specific heat of dry wood.................	= 0.33	B.t.u. per lb.
Latent heat of steam at 212°..............	= 970	B.t.u. per lb.
Latent heat of steam at 307° (60 lbs. gauge)	= 904	B.t.u. per lb.

APPENDIX

Special Woods for War Uses

SPECIES MOST SUITABLE FOR EXACTING REQUIREMENTS

The exigencies brought about by the war have made it absolutely necessary to kiln dry much material which heretofore it has been customary to air dry for the same purposes, the normal supply of air-dry stock being altogether inadequate and the time required too short in which to air dry new material. This, however, is by no means an alarming nor a regrettable situation, since the same material can be kiln dried directly from the saw in equally as good condition and in many cases much better condition altogether as to strength, toughness, and freedom from defects. Material requiring a year to air dry can be kiln dried in three weeks and that requiring from 3 to 5 years to thoroughly season can be dried in 3 to 5 months. Strength tests are being made by the Government which prove that the properly kiln-dried material is fully equal to the air-dried in every respect. Of course, it is understood that suitable methods must be used, and the operation intelligently conducted, otherwise serious injury is likely to result. In many cases a strong prejudice has arisen against kiln-dried wood owing to the bad methods which have been used and consequent injurious results obtained.

Not only must green wood be resorted to but substitute species are being urgently sought after.

Of the species called for by the war conditions which must be dried from the green condition and their uses the following are of the greatest importance:

(1) *Airplanes.*—Sitka spruce (density should be at least 24 pounds per cubic foot for the dry (8 per cent.) wood, and having not less than 10 rings per inch) is one of the best woods when strength, stiffness, and lightness are required. It is used for the wing beams and struts and is in great demand in 2- and 3-inch thicknesses. White ash is also largely used for longerons in inch and a half thicknesses. The northern-grown ash of fair density (at least 35.6 pounds per cubic foot for the 8 per cent. dry wood) is considered the best. Some sugar pine is often used in the wing ribs. These should be dried to about 8 per cent. moisture, or for use on the sea coast probably 12 per cent. is ample. It is unsafe to dry too low, as brittleness must be avoided. Some maple and birch are used for certain parts.

For propellers various species are used, chiefly Honduras and Nicaragua mahogany, black walnut, white oak, and yellow poplar (Tulip). Mahogany and walnut are used almost exclusively abroad.

Careful attention must be given to density, freedom from cross-grain and internal stresses (casehardening). A dryness of about 8 per cent. appears to be

suitable for gluing. For this purpose "quarter-sawed" (radial cut) material should be given preference as far as possible on account of small shrinkage and balanced internal stresses, but it is doubtful whether large enough pieces are now obtainable from black walnut for quarter sawing.

(2) *Gun Stocks.*—Black walnut is the universal wood for this purpose. It is usually cut in 2½ or 2⅜ inch planks and the stocks are sawed to rough pattern in the green. These are at once steamed at about 140° for three days to darken the color of the sapwood, the ends are coated, and then they are shipped to the gun makers. Either quarter or flat grain is acceptable, but it must be straight and free from all twist, worm holes, checks, knots, or evidences of decay. The best quality material for this purpose has a density of the kiln-dry wood at 7½ per cent. moisture of 44.5 pounds per cubic foot, but the material varies from 31 to 51 pounds.

Yellow birch (*Betula lutea*) has proved to be a very good substitute. It is, as a rule, slightly heavier and more inclined to warp, but much more easily dried. The best quality birch for the purpose weighs 43 pounds per cubic foot when kiln dry at 7½ per cent. moisture. The average shrinkages from green to perfectly dry condition in volume are 11.3 per cent. for walnut and 16.8 per cent. for birch, based on the volume when green.

Gun stocks should be dried to an average of $7\frac{1}{2}$ per cent. moisture.

(3) *Wagons.*—Escort wagons are made almost entirely of oak and hickory. Some of the parts are 5 inches thick in the rough. Felloes are $3\frac{1}{4}$ inches square in cross section. The former require 4 to 5 months to kiln dry without injury and the felloes about 3 months. Dry wagon stock to 8 or 10 per cent.

Other species used in wagons are ash, rock elm, maple, and birch; also yellow pine, sap gum, and other soft woods for the boxes.

(4) *Shuttles.*—The increase in demand for cloth has called for such an increase in shuttles that green wood must be resorted to. Dogwood and persimmon are the only two species universally used for shuttles in this country. In Europe boxwood is considered the finest material. These woods can be successfully kiln-dried, but a slow process is necessary at low temperature. About 5 per cent. moisture is a suitable condition to which to be dried. Applewood is recommended by some manufacturers as a substitute. Hop hornbeam (*Ostrya virginiana*) appears to be equal to dogwood in every respect, but is not abundant. It is suggested that some species of eucalyptus growing in California (*E. sideroxylon,* or *E. rostrata*) might make good substitutes, as also Jarrah (*E. gomphocephala*) and other species which, however, are not available in this country.

entirely of green wood it is conceded that air-dried material will make the most durable ships. Furthermore, a ship built of partially dried wood will tighten and stiffen up when placed in the water. The "standard" ships are made almost entirely of southern yellow pine or of Douglas fir.[1] Very little else is used. Large sized material is called for, much of the yellow pine being 14″ × 14″ and 30 to 50 feet long, and running as large as 16″ × 24″ for some parts. In Douglas fir considerable material 20″ × 20″ and 20 to 50 feet long is required.

Some white oak is used, in such places as the rudder post, shaft log, stern post, keel shoe, and at the turn of the bilge. Knees are usually of live oak, white oak, tamarack, spruce, cypress, or white cedar, and are cut from the crook in the log near a root. Treenails are generally made of white oak or black locust. Osage orange should be equally good for this purpose.

In drying, the ceiling appears to be the most important, and it is probable that a dryness of 15 or even 20 per cent. is ample, as this will allow a slight swelling when the ship is placed in the water.

Instructions already given in Table XVI, for drying the various species, should be modified, as noted in the footnotes on page 278, for all special uses where strength and toughness are of vital importance.

[1] For information and specifications address "Emergency Fleet Corporation, U. S. Shipping Board, Washington, D. C."

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